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ECPRI TIMING MEASUREMENT AND TESTING FOR 5G NEW RADIO

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"Anyone can talk about 5G. We are creating it!"

ZENIR M. (2020) . University of Oulu, Degree Programme in Computer Science and Engineering, 81 p.

ABSTRACT

Ultra low latency, increased reliability, massive network capacity, and perpetual availability are what make the 5G not just a network evolution, but a paradigm shift. Nowadays, multiple-input multiple-output , beamforming, wide bandwidth, and multi-carrier aggregation are the key enablers of the next generation of radio access technology (RAN). One of its integral part names, Base Station (BS), maintains the communication between the Network and the mobile users. The BS consists of two major elements. First, the Radio Unit transceiver module which is responsible for radio frequency processing of transmitted and received signals. Second, the Baseband unit which is charged with the digital processing of transmitted and received signals. The interface linker between these two functional blocks is called The fronthaul. To bring more agility on the Network, ORAN alliance introduces an openness concept stretched out to create an open fronthaul based on the eCPRI Protocol. Hence, the antenna data needs to be carried over longer distances introducing strict throughput latency, jitter sends, timing, and synchronization requirements. The main goal of this thesis is to guarantee the proper reception of data over the eCPRI interface, and to ensure that the RF product fulfills the ORAN requirement from a timing point of view. To achieve this target, a study process has been followed. The first phase focuses on studying the main 3 components of the environment represented by BBU 5GNR and eCPRI protocol. In the second phase, the research goes deep in the Radio module and eCPRI protocol delay management and timing, based on the ORAN specification. Finally, we define an algorithm branched out to Test Cases that can validate the 5G Radio module from Timing point of view, once they are all passed. The Test algorithm has been designed also to detect any excess in timing requirement defined by the ORAN Alliance specification. By arranging a good test plan, the algorithm has proven its high efficiency for 5GNR examination from Timing perspective.

Keywords: 5G, 5GNR, Delay management, Timing measurement, Fronthaul, eCPRI, ORAN, Testing, Validation.

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FOREWORD

This thesis was carried out at Nokia "Home of Radio" in Oulu, as a part of my Master's Computer Engineering degree at University of Oulu, Finland. Several persons have contributed academically, practically and with support to this master thesis.

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Oulu, June 15th, 2020

Maher ZENIR

LIST OF ABBREVIATIONS AND SYMBOLS

3GPP	The third generation partnership project
4G	Fourth generation
5G	The fifth generation
AxC	Antenna carrier
BBU	Baseband unit
C Plane	Control plane
CP	Cyclic prefix
CPRI	Common Pulblic Radio Interface
CU	Central unit
D2D	Device-to-device communications
DL	Downlink
DSP	Digital signal processing
DU	Distributed unit
eCPRI	Enhanced Common Public Radio Interface
eNB	e NodeB (applies to LTE)
eRE	eCPRI radio equipment
eRE	eCPRI radio equipment
EVM	Error vector magnitude
eREC	eCPRI radio equipment control
FCAPS	Fault, Configuration, Accounting, Performance,Security
FFT	Fast Fourier Transform
FIR	Finite Impulse Response
GM	Grandmaster
GPS	Global Positioning System
GSM	Global System for Mobile communications
gNB	G NodeB (applies to NR)
IEEE	Institute of Electrical and Electronics Engineers
IFFT	Inverse Fast Fourier Transform
IP	Internet Protocol
LAA	Licensed assisted access
LSB	Least significant bit
LTE	Long term evolution
M plane	Managemnt plane
MMC	Machine-to-machine communications
MIMO	Multiple input multiple output
ML	machine learning
NR	New Radio
O-DU	ORAN Distributed Unit
O-RU	ORAN Radio Unit
O-Cloud	ORAN Cloud
OFDM	Orthogonal Frequency Division Multiplexing
ORAN	Open radio access network
PDV	Packet Delay Variation
PNF	Physical Network Function
PRACH	Physical radio access channel

PRB	Physical Resource Block
PTP	Precision Time Protocol
REC	Radio equipment control
RE	Radio equipment
RF	Radio Frequency
RTC_ID	Real-time Control Data identifier
RRU	Remote Radio Unit
RU	Radio unit
SCS	Subcarrier spacing
SEC_ID	Sequence identifier
SMO	Service Management and Orchestration framework
S plane	Synchronization plane
TDM	Time division multiplexing
UL	Uplink
WCDMA	Wideband Code Division Multiple Access

μs	microsecond
b	bit
Mbps	Megabit per second
Gbps	Gigabit per second
GHz	Gigahertz
kHz	Kilohertz
MHz	Megahertz
ms	millisecond
ns	nanosecond

1. INTRODUCTION

All previous wireless communication generations: 1G, 2G, 3G and 4G, have revitalized human life. When it comes to 5G it is easy to think it is just another G, although it is not. Connecting millions of devices and enabling innovation in smart homes, the fifth generation (5G) is considered as a real network revolution taking humanity far beyond simple mobile uses. The latest evolution of wireless communication is based on five brand new technologies: millimeter waves, small cells, massive multiple input multiple output (MIMO), beamforming, and full-duplex. Behind the scene a radically new distributed network architecture is required to meet the needs for such performance. To achieve that, five key end-to-end enablers resumed in : 5G networking, distributed cloud, network slicing, security, and finally industrial automation. The 5G network overview is illustrated in Figure 1. Basically its

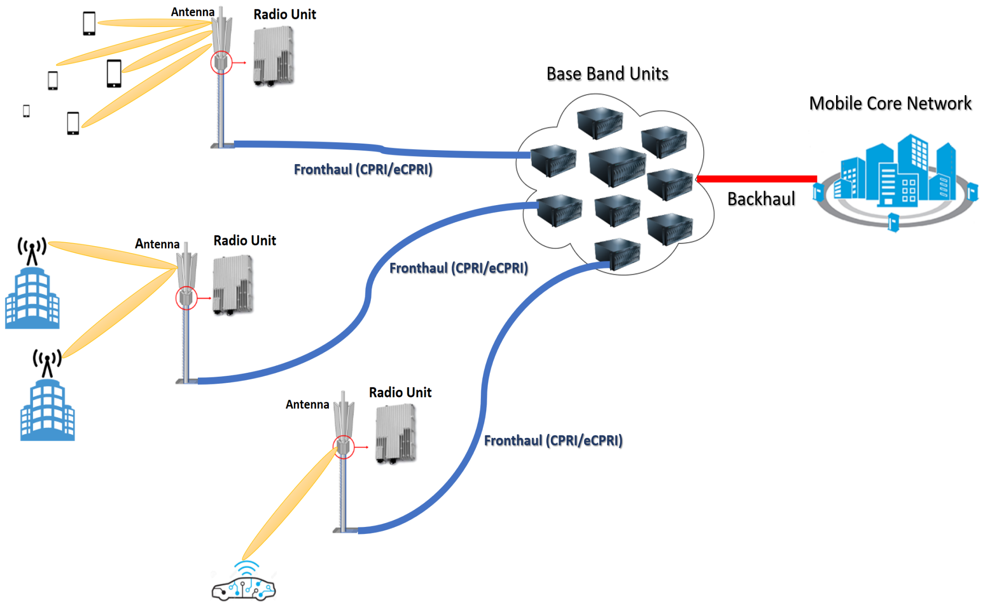

Figure 1. 5G network architecture.

architecture is divided into two fundamental entities. Radio access network(RAN) connected to Mobile core network through a backhaul link. The mobile core network is formed by a cloud platform and then connected to the internet and several service providers. The radio access network is the part that connects user equipment to other parts of the mobile network via a radio connection. It comprises several interconnected radio base stations and antennas. The wireless base station transmits and receives communications between the user equipment and the mobile core network. It is divided into two logical entities. First, the radio unit (RU) which is responsible for the modulation , demodulation of the transmitted and received signal. Whereas the baseband unit (BBU) handles radio communication and radio control processing and digital data processing. The BBU and RU are usually geographically separated, linked only by an interface commonly referred to as the fronthaul. This interface is a fiber-based connection ensures the stream of data between the RU and the BBU. The Common Protocol Radio Interface (CPRI) and enhanced Common Protocol Radio Interface (eCPRI) are considered as the main fronthaul protocols of 5G base stations.

In order to provide more agility and flexibility to the network, Open Radio Access Network (ORAN) alliance has introduced openness, interchangeability, and smartness to the RAN. This openness has stretched out to the Fronthaul. To achieve this target, eCPRI protocol used for its openness, high data rate capability and the ability to cover all ORAN specifications and 5G technologies key characteristics as well. In contrast to the serial interface known as CPRI, eCPRI enables efficient and flexible radio data transmission packet-based fronthaul transport networks like IP and Ethernet. Openness of the network requires a strict synchronization and timing mechanism like Precision time Protocol (PTP) between the RU and the BBU to ensure appropriate transmission and reception of data packets. Timing alignment accuracy between antennas of the same BS as well as of different nodes is required to perform efficient deployment of 5G functionalities like Beamforming and MIMO. For this reason, ORAN alliance and 3rd Generation Partnership Project(3GPP) organization have defined a strict timing and synchronization requirements for every part of the Radio access network to prevent any improper transmission and reception of data packets. The question is how to examine and validate the Unit from a timing point of view? And how to detect any excess of timing fulfillment from the Radio product? What is the process followed to cover and check all transmission possibilities and their conformity to 3GPP and ORAN timing specifications?

This thesis research project is aiming to define examination and verification algorithms to ensure that RF products (RU) fulfill the ORAN and 3GPP requirements from the timing point of view, which implies a proper reception and transmission of data over the eCPRI fronthaul interface. As the functional split of eCPRI is selected a bit earlier, than a frequency IQ data is transmitted over the eCPRI packet which narrowed on the timing measurement there. Also the complexity of 5G New Radio design and the wide range of features provided by 5G technology, have expanded the research boundaries topic to cover more options with different timing terminology.

In the context of solving the problem, a research road map is introduced. The first step was to study the environment surrounding the subject by studying the 5G radio Baseband Unit and eCPRI fronthaul Second, the research goes to focus deeper on the delay management and timing subject, and their requirements defined by ORAN Alliance specification. The third step was an investigation of each requirements' purpose and on what it is based on. Finally, we tried to find the connectivity tool between the requirements defined in the specification and what real product behavior would be after executing the algorithm.

The thesis starts by introducing the two main blocks in our research environment: 5G new radio and Baseband unit, where important functionalities and features of each module are mentioned, as well as a high overview of their timing and synchronization (Chapter 1). In the next chapter, the ORAN concept has been presented, focusing on the most important details that could contribute to timing and fronthaul delay management. In Chapter 4, detailed structural study of fronthaul protocols, namely CPRI and eCPRI is conducted. Furthermore in Chapter 5, the theory of eCPRI timing and delay management has been explained thoroughly based on the eCPRI and ORAN alliance specifications and requirements. Moreove,r Potential algorithmic solution design, implementation, execution, verification and result illustration are presented in Chapter 6. Last but not least, algorithm test results are discussed in Chapter 7. Finally, Chapter 8 summarizes the whole research project work.

2. 5G BASE TRANSCEIVER STATION

2.1. 5G New Radio

2.1.1. Why Do We Need a New Radio?

5G will support countless emerging use cases with a high variety of applications and variability of their performance attributes. 5G requirements imply heterogeneity in multiple areas, from delay-tolerant video applications to ultra-low latency, from highspeed entertainment applications in a vehicle to mobility on demand for connected objects, and from reliable applications to critical ones, such as health. It is also expected that future networks will be able to support thousands of devices, that is to say, machines and smartphones. A flexible system that can adapt the amount of overhead and signaling is desirable. Many current and future applications generate small packets. It includes real-time gaming, instant messaging, machine type of traffic, and status update message. Ultra-dense networks need to handle a large number of simultaneous transmissions in a small geographical area. This poses new challenges to resolve multiple access problems efficiently and flexibly, especially in scenarios where device-to-device (D2D) communications and massive sets of machine-to-machine communications (MMC) take place.

5G will operate in a highly heterogeneous environment characterized by the existence of multiple types of access technologies: multi-layer networks, multiple types of devices, multiple types of user interactions,..etc. In such an environment there is a fundamental need for enablers to achieve seamless and consistent user experience across time and space. Clearly the 5G architecture should include modular network functions that could be deployed and scaled on-demand to accommodate various use cases in an agile and cost-efficient manner. 5G promises to improve wireless network performance by providing the capacity to support diverse connections and the flexibility to adapt to each user's needs. Consequently, 5G requires much more scalability and flexibility than previous generations. Current wireless standards, such as LTE, while providing significant enhancements over previous generations will not be able to fully meet these challenges. The existing design is geared towards one size-fits-all solution, which is not flexible and efficient enough for the variety of applications and services in a vision for the future. A single monolithic air interface design will not be able to suit the competing needs of different applications. When designing the future air interface considerations are taken to address several key challenges, in particular: latency, overhead, capacity, spectral efficiency, number of users, high-reliability, ubiquitous coverage, high mobility, massive number of devices, and low cost and energy consumption..etc. With all these requirements and the diversity of solutions, flexible design and interface management are of increasing importance as most likely a one-fits-all solution will not be able to efficiently address all the demands of the diverse services of future wireless networks. There is a consensus that there will be a new non-Backward Compatible radio as part of next-generation radio technology clearly the 4G air interface and its evolution fall short in meeting the requirements of the new use cases. There is an obvious need to shape a new 5G air interface that will offer much more than just a faster variant of 4G.

2.1.2. Key Characteristics of 5G New Radio

To allow the system to adapt to the anticipated wide range of use cases and extreme requirements. The key characteristics of 5G new radio should be flexibility scalability efficiency and reliability. The flexibility of 5G radio will allow the support of a multitude of applications with diverse requirements. The use cases for 5G will be more diverse than ever and will require very diverse link characteristics. Some examples are: massive data transmissions that require large packet sizes and a lot of allocated resources. Nonstationary sensors may need only small packet sizes and rare resource allocations, but in turn, require a battery efficient sleep mode. Flexible adaptation to fast traffic variations in Uplink and Downlink. Cloud gaming or remote machine control requires low end-to-end latency. Video streaming requires latency matching with the data array communication systems beyond 2020 will need to be flexible enough to accommodate all the diverse use cases without increasing the complexity of management. Another reason, the flexibility is the first key design principle of 5G is that any new technology or system we design for 5G needs to be future proof, and last at least until 2030.

Reliability as a key design principle for 5G ,is related to flexibility with the flexible integration of different technology components, we will see a step-away from best effort mobile broadband towards truly reliable communication. Reliability is not only about equipment up-time, but it also relates to the perception of infinite capacity and coverage that future mobile networks need to deliver. This in principle means that for all use cases in the vast majority of the users, the required data will be received in the required time, and will not be dependent on the technology used. Furthermore, reliability is becoming more critical as we start to rely on mobile communications for control and safety. A reliable connection can be defined as the probability of a certain data package being decoded correctly within a certain time frame. This means that retransmission may be needed to ensure the reception of a correct data package, a process that will inevitably delay the transmission. Therefore, even to obtain LTE latency numbers with higher reliability a lower system delay will be required. Putting reliability as a key design principle for 5G, means that in all concepts of system design focus should be put on fairness. The requirement is expressed in the percentage of the users and not the locations of coverage. Because even the reliable network needs to be cost-effective for the service providers. The mechanisms for a trade-off between link reliability, solo packet error rate, and throughput or latency are introduced in a simple and efficient way. Multiple network layers and radio access technologies are used to provide the most reliable link, based on the user's application needs, location, and mobility.

2.1.3. Massive MIMO and Beamforming

Massive MIMO, also known as large-scale antenna systems, very large MIMO, or hyper MIMO, is becoming mature for Wireless Communications and has been incorporated into Wireless Broadband standards like LTE and Wi-Fi. Basically, the more antennas the transmitter-receiver is equipped with, the more possible signal paths and the better the performance in terms of data rates and link reliability. The price to pay is increased complexity of the hardware, a number of RF amplifier front ends, and the complexity and energy consumption of the signal processing at both ends. Massive MIMO techniques are at the heart of achieving higher capacity for Cellular Systems. It is based on antenna arrays with a few hundred antennas simultaneously serving many tens of terminals in the same time-frequency resource. The basic principle behind a massive MIMO is to reap all the benefits of conventional MIMO but on a much greater scale. Multi-User MIMO. MU-MIMO offers increased multiplexing gains, and even though it has been included in the 3GPP LTE advanced standard, its full potential has yet to be realized. Drastically higher capacity can be obtained by very large MIMO via arrays employed at the base station. Increasing transmit array size has desirable implication for coverage., intra-symbol and inter-cell interference control, and transmit power budget optimization Massive MIMO was originally envisioned for time division duplex (TDD) operation, but can potentially be applied also in frequency division duplex (FDD) operation. Other benefits of massive MIMO include the extensive use of inexpensive low power components, reduced latency, simplification of the media access control (Mac layer), and robustness to interference and intentional jamming. The anticipated throughput depends on the propagation environment providing asymptotically orthogonal channels to the terminals, and experiments have so far not disclosed any limitations in this regard. Integrating large scale antenna arrays into the air interface design of 5G systems in the centimeter wave or the millimeter-wave bands will show significant differences to the MIMO solutions currently deployed in 4G systems.

Massive MIMO can be used to improve spectral efficiency via multi-stream transmission, or to form a narrow beam to increase transmission distance. Sub 6GHz bands have smaller bandwidth, but massive MIMOmulti-stream transmission can achieve high gigabits per second peak data rates. Antenna size is inversely proportional to the frequency. So the antenna's physical size will set a limit on the possible number of antennae elements. Higher bands have relatively large bandwidths, but also greater path losses. Massive MIMO is an effective way to compensate path loss on 3 - 40 gigahertz bands using High beamforming gain as well as to increase the peak data rate by multi-stream transmission. For very high-frequency bands such as millimeter-wave 30-100 GHz, the antennae will focus their energy towards the receiver to overcome increased path loss caused by radio application.

2.2. Base Band Unit

2.2.1. What Is a Base Band Unit ?

Baseband or lowpass refers to a signal that exists within a frequency range near to zero and negligible elsewhere. Baseband signal travels at its original frequency spectrum through complex trajectories and without any modulation or shift in frequency[1].

To interpret baseband frequencies in telecommunication systems a baseband unit is used connected over optical fiber to RRU (remote radio unit) which represents the RF system . BBU is known for its easy deployment and low power consumption, it performs many functions and plays as a switchboard linking multiple nodes in the network[1].

2.2.2. Characteristic of a Baseband Unit

Global System for Mobile Communications (GSM), wide-band Code-Division Multiple Access(WCDMA), LTE or 5G BBU (AirScale system module Nokia name) are all supported either single-mode or in multiple modes (up to 3 technologies simultaneously) with a throughput of 84 Gbps and more [2]. In Addition BUUs are able to be used in chaining mode covering up to 6 terabits per second. This capacity scales up to huge connectivity that serves growing IOT technology and all 5G applications. The baseband device is modeled in a way where energy can be minimized during zero processing tasks. Furthermore, BBUs can be connected to several remote radio heads at the same time, contributing to cost-saving, less cabling and complexity.

2.2.3. Base Band Unit Functions

Linking BBU to RRU will form a transceiver base station (gNodeB in 5G network). In this area BBU is known as the brain since it links between two-end users. BBU provides a common interface to connect with radio units called Fronthaul Transport Network. In This part of the network, BBUs are the masters. Several protocols are used to communicate between the two nodes; the latest most used ones are CPRI and eCPRI . Through those protocols, BBU is able to communicate and transmit baseband signals with high rate throughput in a downlink way. In uplink direction, the baseband unit captures the radio signal over optical fiber. Over there, processing blocks, baseband signals, or real information are extracted from such frames or data received.

Synchronization and time-alignment are the most important rules which the nodes should follow in the network. Inside the BTS BBUs should always keep synchronization with radio units and even the BBU chain inside the same BS. Furthermore, management, operation, and maintenance inside BTS is a BBU responsibility, such that it tries to organize the connection between modules inside and outside the base station and always ensure the connection to other cells in the network, wrapping signal message processing and alarms in case of error or fault in the system.

2.3. Base Station Timing and Synchronization

2.3.1. Concept

High speed data services is always a target for operators and a need for users especially professionals. The quality of synchronization has a direct impact into the Quality of Service. In Addition, for telecommunication system performance, radios need good synchronization to achieve a suitable separation and avoid channel interference. Moreover, there is a high exigency for Synchronization in Handover. In such a way Low synchronization influence the matching frequency between the adjacent cell [3]. High accuracy time/phase synchronization becomes important for new technologies 3g and LTE . CDMA , TD-SCDMA ,TD-LTE requires microseconds accuracy between neighboring base station. Previously Global Positioning System (GPS) was used as a tool to achieve alignment. However the high cost and limited satellites source obstruct the connectivity for the huge number of base station needed for the modern telecommunication technology. This issue drives to look for alternative solution by delivering timing information via transport networks using a synchronization, where PTP was found as a solution [4].

2.3.2. Timing and Synchronization Requirement

The different type of transmission and communication in the network requires different limits for the synchronization. Since FDD (frequency Division Duplexing) two separate communications channels.FDD has a need for frequency synchronization. to work accurately 50 ppb of frequency error is a necessity. As a result, handover is supported, and switching from cell to another is safe.

In Time Division Duplexing (TDD) single frequency for transmission and receiving is used. the frame structure in TDD handles both downlink and uplink at the same frequency with the different time slots and between every DL and UL (switch) guard band is required. In addition to the guarantee of channel alignment. Hence this network needs a high precision time and also phase synchronization which should not go above the microsecond level. usually, GPS is used in this Duplex type due to its high accuracy estimated to 100 nanosecond. to provide GPS for base stations outdoor antenna is required to receive the satellite transmissions [5].

3. OPEN RADIO ACCESS NETWORK

3.1. ORAN High-Level Overview and Functionality

Openness and Intelligence are the main targets of Open RAN technology, leading the network to be more virtualized and open, enabling multi-vendor deployment, interface interpolation and Hardware minimization. Moreover, Artificial intelligence (AI) and big data decrease the complexity of the 5G network by deploying self-driving and learning networks that replace human-intensive. Service Management

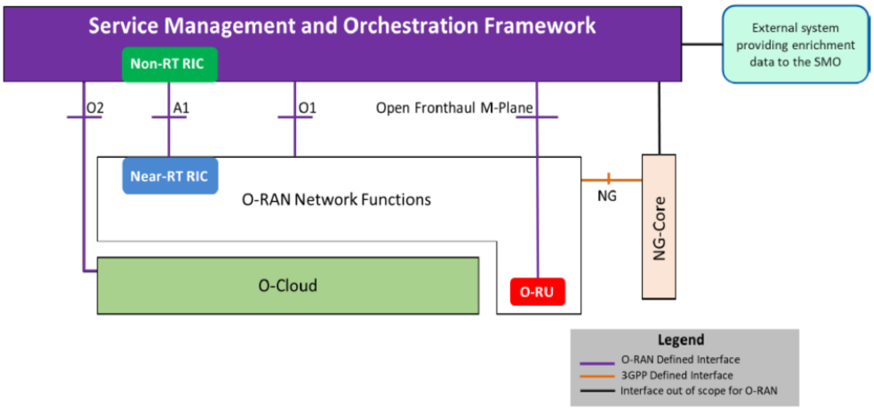

Figure 2. ORAN overview[6].

and Orchestration framework or SMO provides performance fault and configuration management. More than that, SMO provides utilities such as Physical Network Functions (PNF) and software management. All those services are provided through four different paths :

- O2 interface between the SMO and the O-Cloud to provide platform resources and workload management.
- A1 Interface between the O-RAN non-real time RAN Intelligent Controller(Non-RT RIC) in the SMO and the Near-RT RIC for RAN Optimization.
- Open Fronthaul M-plane interface between SMO and O-RU for 4 FCAPS support.

As discussed earlier artificial intelligence is considered one of the fundamentals pillars of the ORAN technology. Non-Real Time RAN Intelligent Controller (Non-RT RIC) is a supporter of AI and machine learning (ML) management and optimization for the RAN. For this node, SMO is considered as the B-Data provider for AI training.

Over the O2 interface, SMO provides support for the orchestration and work flow management of the O-Cloud part. O-Cloud handles software components including operating systems and virtual machines. To provide life cycle management and infrastructure discovery, the O-Cloud part supplies ORAN cloud and workload to the network over O2.

The open fronthaul interface linking ORAN-distributed unit (O-DU) and ORAN radio unit (O-RU), includes 3 major planes to ensure the reliable connection between digital unit and Radio units. The S plane known as synchronization plane, plays the role of synchronizing the two nodes enclosed time, phase, and frequency synchronization. Moreover, the Management plane (M plane)is responsible for supporting FCAPS(Fault, Configuration, Accounting, Performance, Security) to the O-RU. The two last and important planes are the Control plane (C plane) and User plane (U plane). These two are mainly covering the data configuration and feature parameters and the Actual data desired to be sent by the users respectively[6].

3.2. ORAN Architecture and Requirement

Telecommunication base stations (BS) are formed by two principle nodes, in ORAN specification known as O-DU and O-RU. The digital or central unit handles the digital signal processing (DSP) and baseband processing. It is assigned to control the operation of the RU and the real-time of the C and U plane to carry data properly to the O-RU.

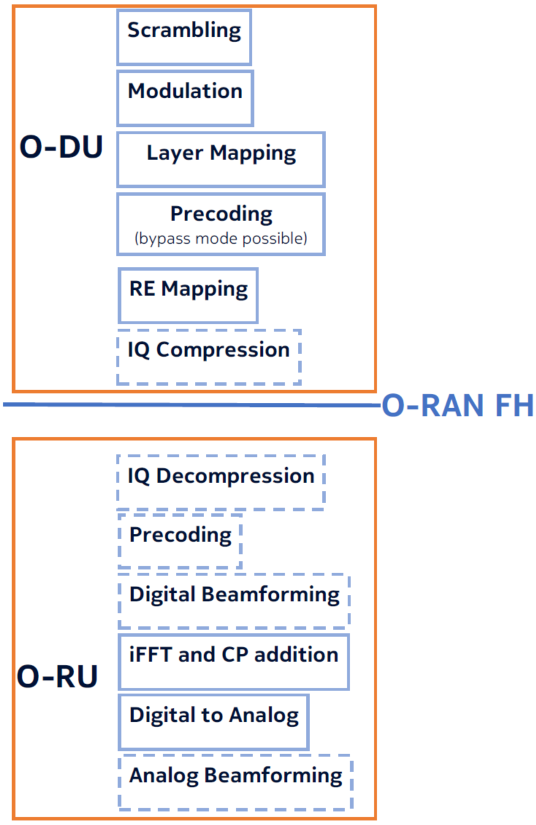

Figure 3. Functional split[7].

Besides, the O-RU is the latest node that connects to the UE in the Open RAN Network. Basically, O-RU processes the data received from the O-DU and outputs IQ data as radio-frequency signal over the antenna. ORAN has chosen a functional split in between the O-RU and O-DU so that the radio unit complexity, weight, and height power consumption are minimized. At the same time O-DU processing is reduced. The 7-2x split dedicated to the ORAN architecture shown in Figure 3 has split the O-RU into two categories, depending on where the precoding function is located. A category of precoding processing is not supported in O-RU therefore any beamforming activity in O-RU will exclude the precoding calculation. Moving the decoder part one step down to O-RU will create new complications and differ technology and test models one from the other . For instance, control plane instruction is different in the case of LTE test model(TM2),TM4 which will need additional instruction compared to LTE TM5-10 and New Radio(NR).

3.2.1. Downlink ORAN Functional Split

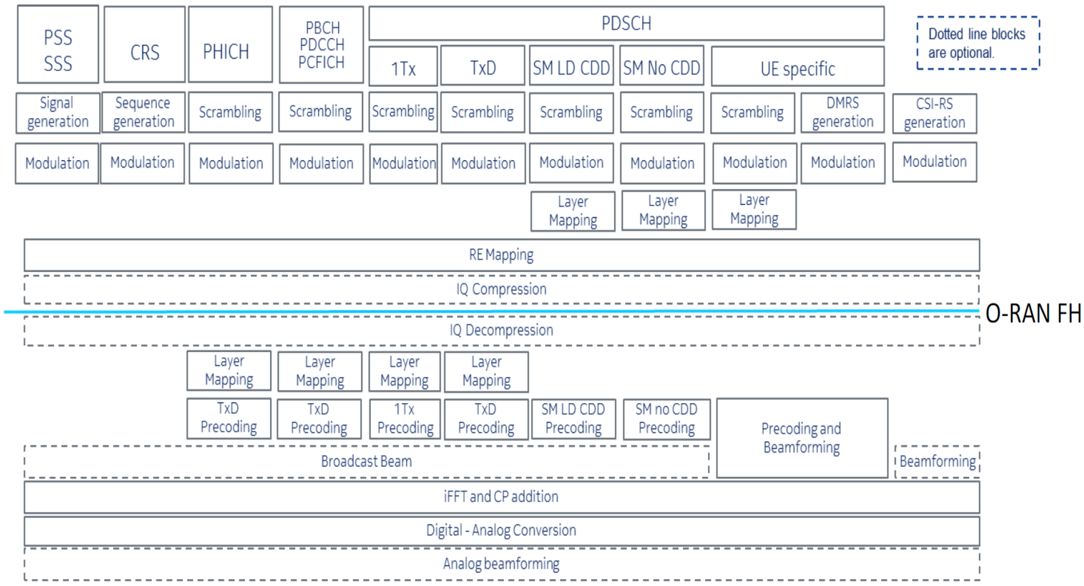

Figure 4. Downlink Functional split[7].

In the DL case as depicted in Figure 4. O-DU handles the modulation functionalities and scrambling of the data. After that, the data will be mapped over the RF mapping and finally compressed over the IQ compression module and transferred as IQ samples over the O-RAN fronthaul, which typically uses eCPRI protocol. Once the data reaches Radio Unit, the extraction of payload data from the decompressed IQ streams begins. So that, it is reliable to precode and pass it over the Inverse Fast Fourier Transform (IFFT) blocks to switch to time domain. Finally data streams move to the analog part and the beamforming phase where the transformation to per antenna streams occur.

The 7-2x split has simplified the fragmentation and management at the transport level. So that for U plane data are transferred by resource elements and resource blocks and OFDM symbol principle. Moreover, this lower split allowed the optimization of transport bandwidth by sending Physical Resource Block (PRB) containing U plane data only. As shown in the Figure 4, most of the functions are in the O-DU part. This had allowed the software update to replace the hardware changes at the O-RU in case of new development or new additional features[7] .

3.2.2. Uplink ORAN Functional Split

In the UL direction, the O-RU receives the wireless signal over antenna elements which should be arranged. Passes through analog beamforming block and Analog to Digital Converter block data would be ready to be converted from time to frequency domain by the Fast Fourier transform (FFT) block. Afterwards, basic filtering and digital beamforming are handled to extract the actual data that will be compressed in the next step as IQ data again.

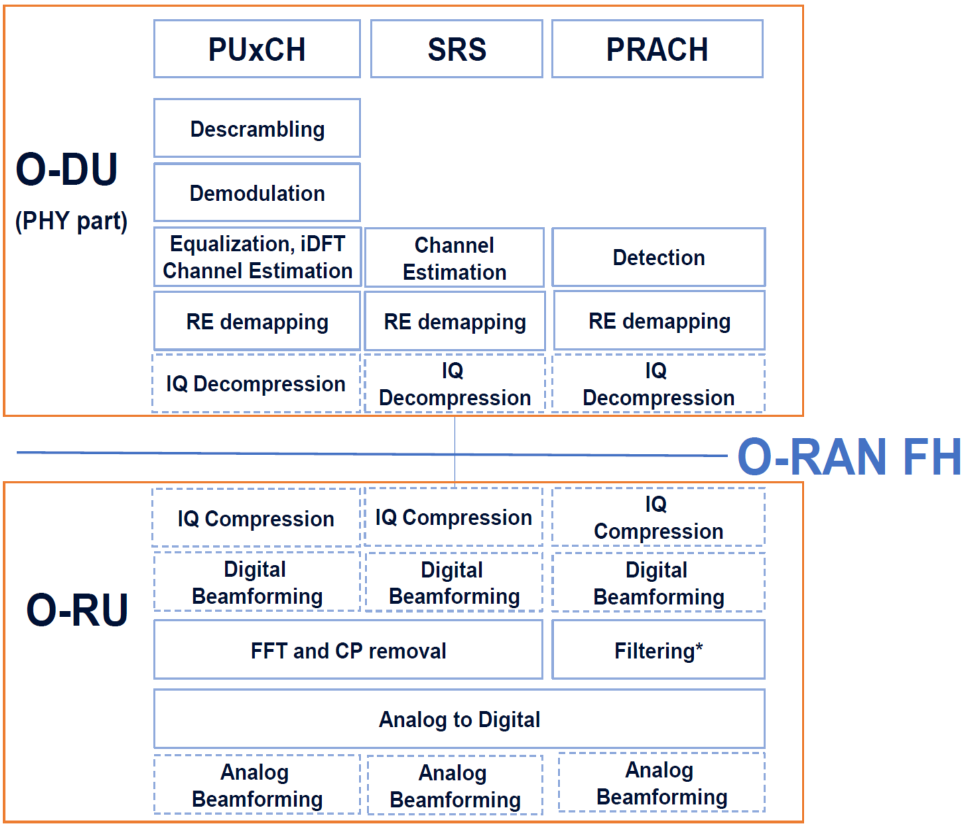

Figure 5. Uplink Functional split[7].

Transmitted over the O-RAN fronthaul, the IQ data which represent the output of the O-RU in UL direction will be decompressed and arranged into resource blocks and further in more processing inside the O-DU.

3.3. Protocol Architecture

3.3.1. Control Plane

Control plane is a type of messages encapsulated over eCPRI or IEEE1914.3 mechanism. Due to the nature of those protocols, messages acknowledgment is not achievable. The Control plane mainly defines the characteristics of U planes.IQ data that corresponds to the same slot number. Generally, the C Plane contains control and synchronization data. Furthermore, it is associated with control information

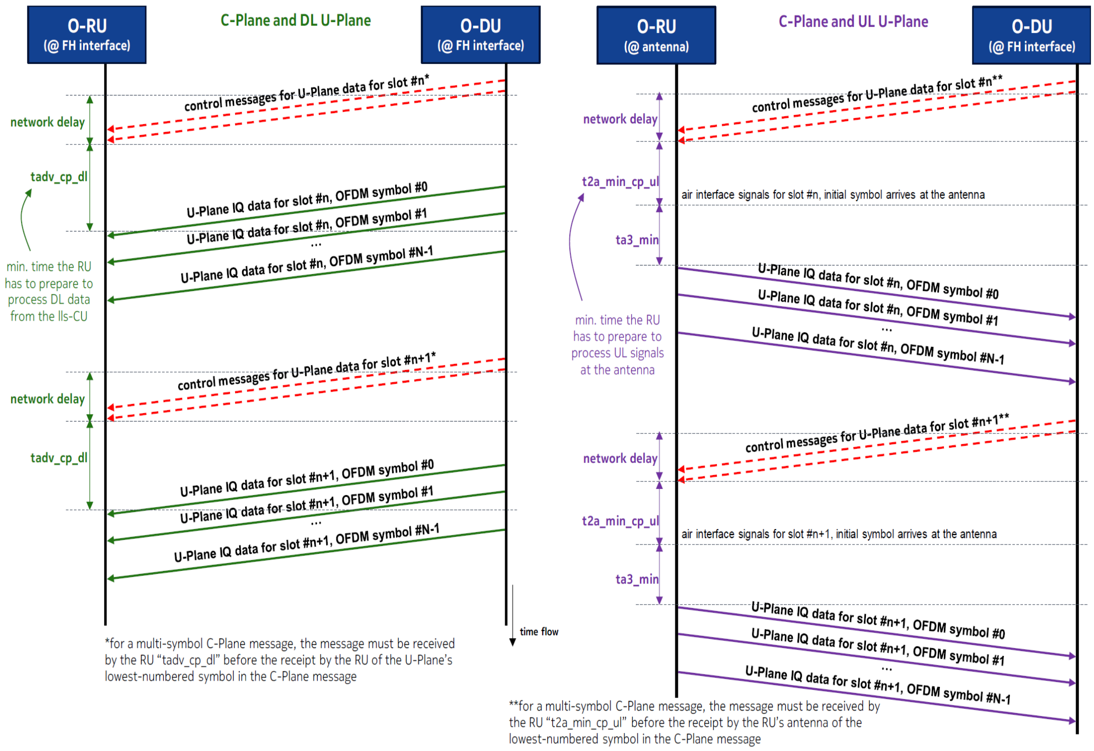

Figure 6. Scheduling and beamforming commands transfer procedure[7].

required for processing user data scheduling, compression, beamforming commands, numerology type and slot id along with other few parameters.

In the beamforming side, the beam coefficient and weights are updated to the O-RU in real time sent over the C plane. The C plane operates as a reporter of measurements, handover execution, handoff control and more. [15]

As depicted in the above Figure 7, C plane is sent separately from the U plane data. For the downlink case, C plane is sent before the U plane with a specific period of time that allows the O-RU to process and be ready for the next received U plane, coming from the same source O-DU. This C plane is sent again for the next slot. Depending on U plane characteristics and patterns, the C plane could be the same copy or reconstructed. Moreover, it could be sent either on one packet or in different ones back on the channel for which information is conveyed. To exchange the C plane between O-DU and O-RU, the command procedure is used. That results to support some features in both nodes.

3.3.2. User Plane

Similar to C plane,the U plane is also encapsulated over eCPRI or IEEE1914.3 mechanism.

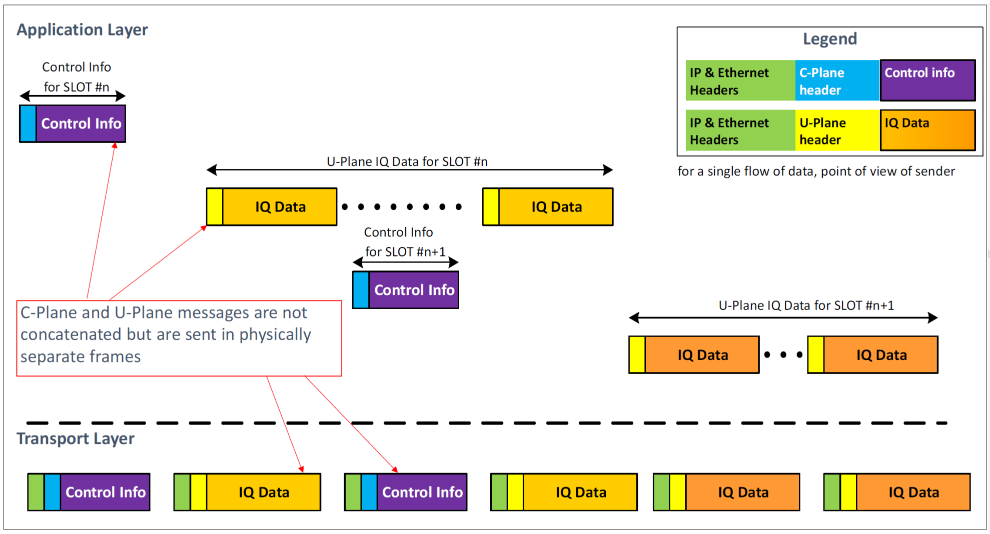

Figure 7. IQ data transfer [7].

Over compressed packets, all IQ data Physical radio access channel (PRACH) and control channels are bundled together based on PRB number. The IQ data is variable with reference to the section and subsection used. As much as subsection the more flexibility in compression is. In some cases, fixed compression is needed. To manage this, the M plane defines the fixed compression method where all the messages would be based.

As shown in Figure 7, the data are in frequency domain known as IQ data samples. The control information packets are sent always before the U plane packets. Every slot C plane packet precedes U plane packet by a certain period of time defined by time management parameters known as Tcp_adv_dl.

This amount of time allows O-RU to update beamforming weights linked to the user data in a DL direction. Similarly, the C plane packet, in UL data flow, is used to adapt the processing of the O-RU for the U plane data coming to its antenna.

The U plane packets are usually separated into two parts. The first defines the scheduling, beamforming commands information followed by the IQ data samples. It is worth noting that the U plane data can actually exceed the maximum ORAN specified packet size. In such cases, the data is split over multiple packets . Typically, data is organized in many section types. Data that belongs to different sections should be sent separately. As much as section and subsection exist, it implies minimization of packets rate. Whenever the I and Q samples are not achieving 1 byte alignment, stuffing bits are added at the end of a section. As discussed earlier PRB are the basis of U plane compression. More than that, U plane parser is expected to be exactly 12 complex-valued RE. All this implies whenever there is a missing even factor of 12 REs padded zero will fill the space to byte boundaries[7].

4. 5G FRONTHAUL PROTOCOLS

4.1. Common Public Radio Interface

4.1.1. Protocol Overview

Common public radio interface is the most used protocol in 4G and early 5G fronthaul. It was established in 2009 by base station vendors such as Ericsson, Nokia, Siemens Network, Alcatel, Lucent, NEC, and Huawei technologies. By replacing coaxial cable by optical fiber to link RRU to BBU, CPRI is used as the protocol carrying data in between .

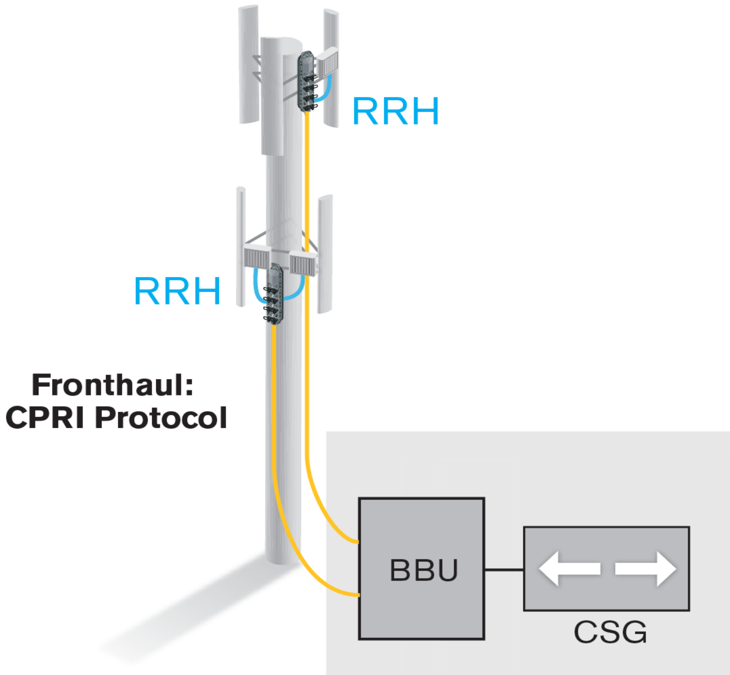

Figure 8. BTS architecture[8].

When getting RF signal in the RRU antenna (uplink direction), the Radio Unit will digitize data and wrap it up into the CPRI protocol (IQ user data) going through the optical fiber reaching the BBU and Backhaul afterward. In the downlink direction, the baseband unit sends user data to RRU enveloped in CPRI protocol. The CPRI frames will be unpacked, converted to analog signal and then transmitted over the air as RF signal. CPRI line can reach 614.4 Mbps and eventually higher[9].

CPRI protocol is divided into 3 layers(Figure 9). Layer 1 and 2 are bounded to transfer user plane control and management and synchronization between the REC and RE, while layer 3 is Vendor specific .

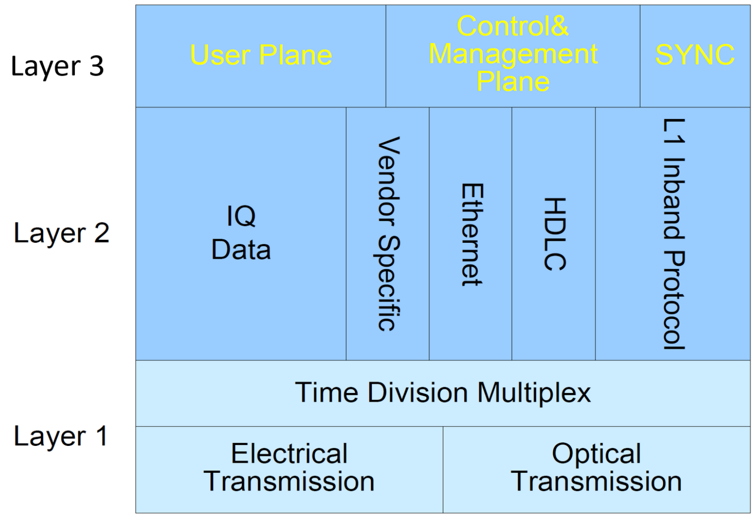

Figure 9. CPRI protocol overview[9].

Layer 1 covers the transmission in both types optical and electrical transmission. The Time Division Multiplex (TDM) part allows transmitting different user's digital signals over one link by dividing timing into slots or intervals. CPRI interface can support several types of information IQ data where most user data are modulated. Synchronization type for time alignment of frame data, control and management data to be exchanged between Radio equipment controller and radio equipment covers high level data link control and Ethernet. Moreover, additional slots for vendor specific allow to add any kind of specific user data, Control and Management (C & M) data. All data types cited above are multiplexed to be transferred using time division multiplexing technique.

To achieve higher flexibility and cost efficiency, CPRI provides 10 different line bit rates and coding. Word width which is the first component of the CPRI frame affects directly the line bit rate as well as the transmission speed. The first option with 1 byte of data for each word will apply 614.40 Mbps per 8b10b line coding (8b10b means 1 word byte is translated to 10 bits). Up to the 10th option word width can achieve 48 bytes with a transmission speed of 24.33 Gbps.

4.1.2. Frame Structure

Radio frame consists of a 10ms time period . It is divided into 150 equal slots named hyper frames. The duration of each hyper frame is 66.7 us . Any individual hyper frame is spit into 256 basic frames with equal time interval of 260 ns.

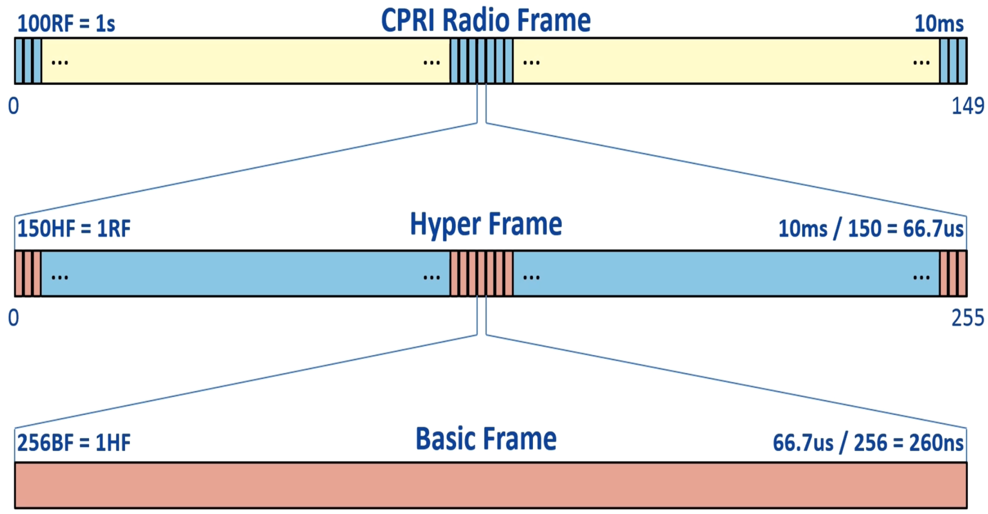

Figure 10. CPRI protocol frame structure.

Lastly ,as illustrated in Figure 10, frame structure of the CPRi protocol consists of the following: 256 basic frames, each basic frame if of 260ns , 256 bf constructs one hyper frame of period 66.7us. A collection of 150 hyper frame takes a shape of 10 ms frame which is the radio frame.

Basic frame

Basic frame is the smallest unit in the CPRI frame it repeats 3.84 million times per second, which means basic frame period is 260.42ns equal to the Chip time (Tc) in radio processing.

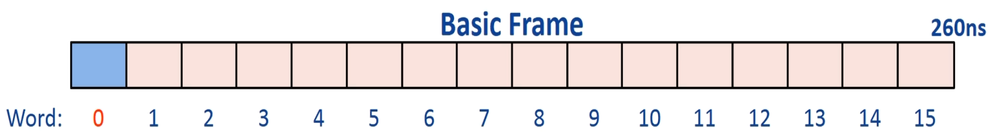

Figure 11. CPRI basic frame.

One basic frame contains 16 word indexing from 0 to 15 . The word index 0 is the control word. The remaining are dedicated to user plane IQ data transport. Word length consists few bytes. Depending on the CPRI option used, the Length can vary from 0 to 48 byte for each single word in basic frame. Diversity of word length is the key on different line rates in CPRI protocol options. The more the word length increases, the bigger the line rate goes. Line rate can be calculated using the following formula :

$$\text{Line bit rate}_{\text{Mbps}} = 1\text{Word length} \times 16\text{Word} \times 256\text{basic frame} \times 150\text{hyper frame} \times \text{line coding} \times 100$$

Note :
line coding in CPRI can be either 8b10b (option 1 to 7) or 64b66b (option 7A to 10). In the above formula byte is interpreted as 10 bits in case of line coding 8b10b, However 8 bytes are considered to be 66 bits for 64b66b line coding (see Table 1).

Table 1: CPRI line rate (adopted from [9])

CPRI option	Word width	Line bit rate	Line coding
1	1 byte	614.40 Mbps	8b10b
2	2 bytes	1228.80 Mbps	8b10b
3	4 bytes	2457.60 Mbps	8b10b
4	5 bytes	3072.00 Mbps	8b10b
5	8 bytes	4915.20 Mbps	8b10b
6	10 bytes	6144.00 Mbps	8b10b
7	16 bytes	9830.40 Mbps	8b10b
7A	16 bytes	8110.08 Mbps	64b66b
8	20 bytes	10137.60 Mbps	64b66b
9	24 bytes	12165.12 Mbps	64b66b
10	48 bytes	24330.24 Mbps	64b66b

To preserve CPRI frame data structure a special indexing is introduced. In ascending order, bits forming the Bytes Word are labeled by 'B' where bit indexing Range is :
$B \in$ [0..(Nx8-1)] where N is the number of Byte per Word.
Y is assigned to Byte indexing within the basic frame [0.. (N-1)].
W defines word indexing 0 to 15.
$X \in$ [0..255] refers to Basics frame indexing in one hyper frame.
Finally $Z \in$[0..149] indexes Hyper frames in a single radio frame of 10 ms.
Table 2 covers indexing for all CPRI protocol options examples :
Z.2.0 = word 0 within basic frame 2 in any Hyper frame in 10 ms radio frame.
0.0.0.0.0 = bit 0 of byte zero of word zero within basic frame 0 within hyper frame 0. This bit represents the first bit in the whole 10ms radio frame.

Table 2: CPRI indexing (adopted from [9])

CPRI line bit rate [Mbit/s]	Z	X	W	Y	B
614.40	0, 1,……149	0, 1,……255	0, 1,……15	0	0, 1,……7
1228.80				0,1	0, 1,……15
2457.60				0,1,2,3	0, 1,……31
3072.00				0,1,2,3,4	0, 1,……39
4915.20				0,1,2, …,7	0, 1,……63
6144.00				0,1,2, …,9	0, 1,……79
9830.40 **8110.08**				0,1,2, …,15	0, 1,……127
10137.60				0,1,2, …,19	0, 1,……159
12165.12				0,1,2, …,23	0, 1,……191
24330.24				0,1,2, …,47	0, 1,……383

IQ data mapping

User plane data is carried in the form of I and Q data blocks. IQ samples are subdivided into I and Q, which refer to the real part and Q to the imaginary part for such data respectively.

The width of each IQ sample can differ from application layer to another. Options available for downlink IQ width is [8 to 20 bits] and for uplink [4 to 20] both I and Q samples should have the same bit width. example : I = Q = 15 bits this implies IQ sample = 30 bit . As shown in Figure 12, IQ samples are mapped interleaved depending on word length T.

Regardless of the line bit rate, basic frame duration remains constant. When dealing with a 1X mode word length of 8 bit, all IQ data are adjacent horizontally. expecting I=Q=8 bits in the duration of 260.42 ns only 15 I and Q samples are separately transmitted. Although for 2x mode and 3x mode 30 and 60 samples are transmitted respectively at basic frame duration.

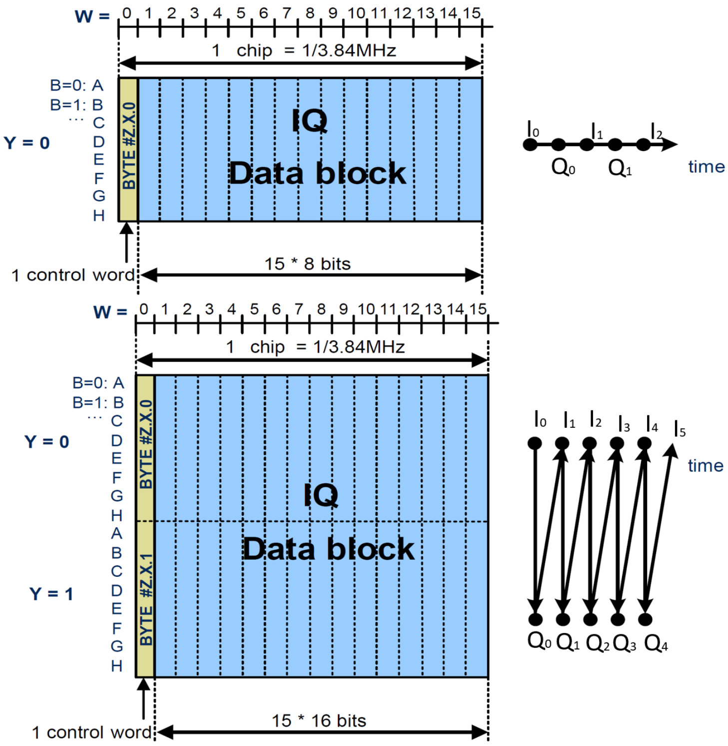

Figure 12. CPRI IQ data mapping[9].

The antenna carrier (AxC) is the area holding some number of sample bits from one or more antennas in one Basic Frame. The size of AxC container (N_{AxC}) should be an even number of bits. AxC containers are mapped following rules for both uplink and downlink. First each AxC Container is sent as a block. Second, overlapping is not allowed in consecutive containers. Third, the unused bits between the AxC container are considered as reserved bits ('r').

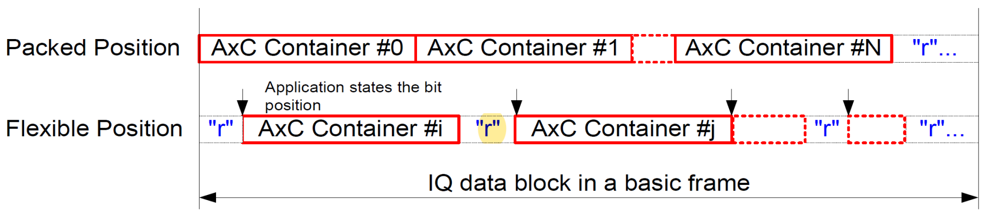

Figure 13. CPRI AxC mapping (adopted from [9]].

As demonstrated in Figure 13, AxC container can be positioned either packed position, where its content is compacted and sent consecutively without any reserved bit in between or flexible position option, where bit gap is introduced (reserved bits) in between the containers. Moreover, the beginning and end bit of each AxC should be specified[8].

Hyper frame structure

As discussed in the previous section the first word of each basic frame is always reserved as a control word. So, the number of control words is equal to the number of basic frames in a CPRI radio frame. In other words, there are 256 control words in the hyper frame. Control words are organized into 64 sub channels (shown in Figure 14) .Each channel composed with 4 control words.

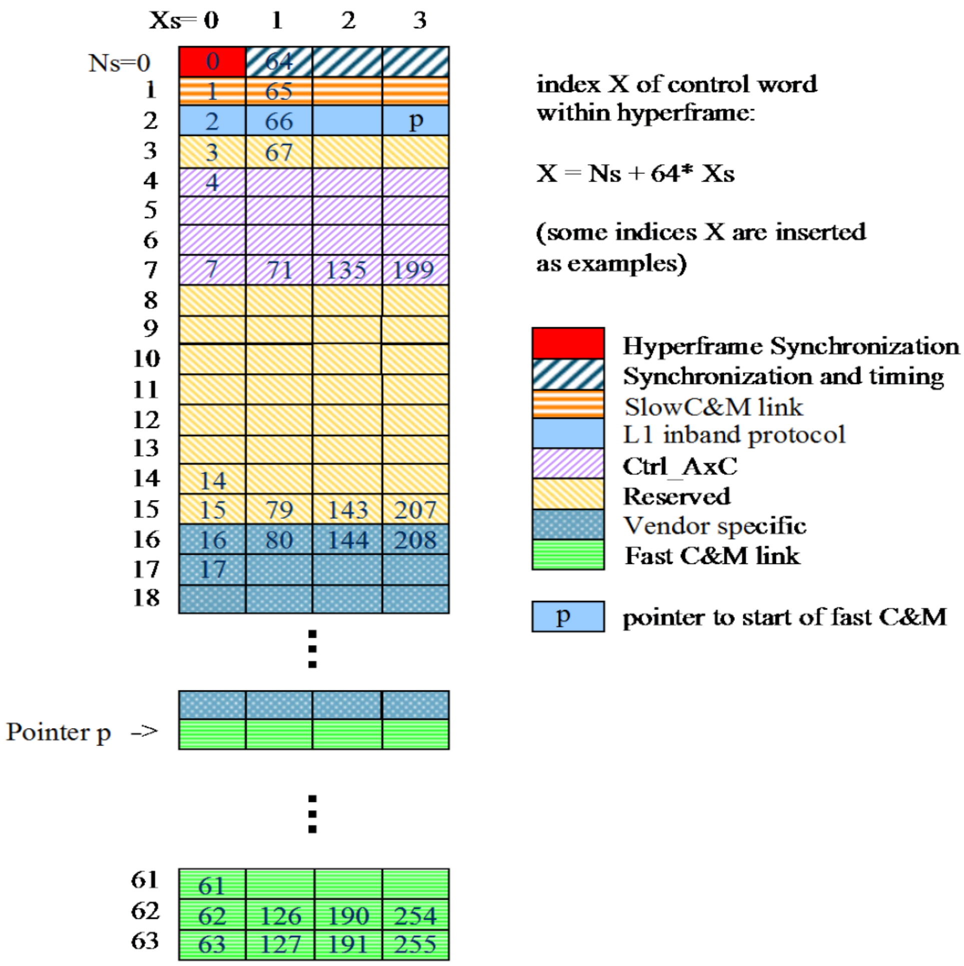

Figure 14. CPRI hyper frame structure [9].

4.2. Enhanced Common Public Radio Interface

4.2.1. ECPRI Overview

To meet the ever increasing throughput requirements along with maintaining ultra low latency in New Radio mobile networks, A packets based fronthaul has been designed to replace CPRI and Open Base Station Architecture Initiative (Obsai) interface. The new internal interface of the radio base station is connecting eCPRI radio equipment control (eREC) and eCPRI radio equipment (eRE). Providing more flexibility in the functional split physical layer part of the radio base station(see Figure 15. On the other hand, eCPRI with a bandwidth capacity of 10 times more than CPRI allows it to use fewer transport resources in 5G network compared to 4G .eCPRI brings flexible radio data transmission through a packet-based fronthaul network, for example internet protocol (IP) or Ethernet. Three planes are necessary for interaction between eREC and eRE. Firstly, the control and management plane for the operation, administration, and maintenance between the nodes. Secondly, the user plane which covers data flow transmitted between Radio base station and user equipment (both Downlink and uplink directions) all associated with its real-time control data.

Thirdly,the synchronization plane deals with data flow for synchronization and timing information in the network. One more important part of the network is the grandmaster (GM) clock, that is located either in the network (outside Base Station) or inside one of the eCPRI nodes (most likely in the eREC). The GM clock acts as a reference clock of PTP based network to synchronize all the nodes.

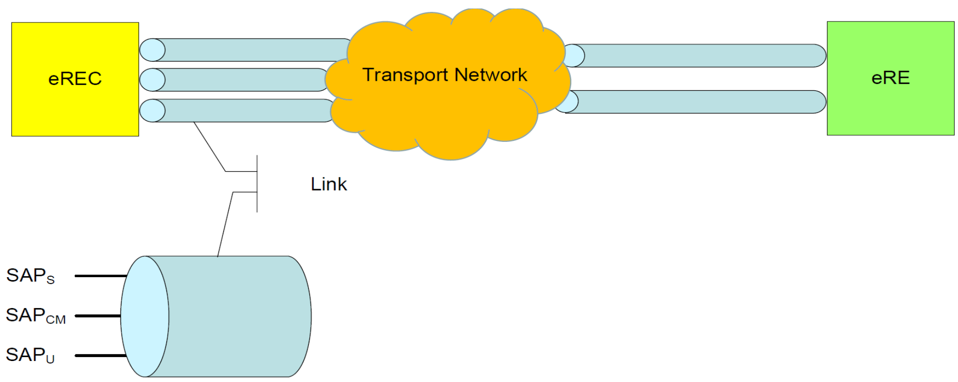

Figure 15. eCPRI basic definition [10].

4.2.2. Functional Description

As discussed earlier in Chapter 3 the functional split inside the Base station will impose strict constraints on both eRE and eREC as well as the fronthaul interface in between. When CPRI fronthaul was used, the split was on option 8 (E in Figure 16) where the

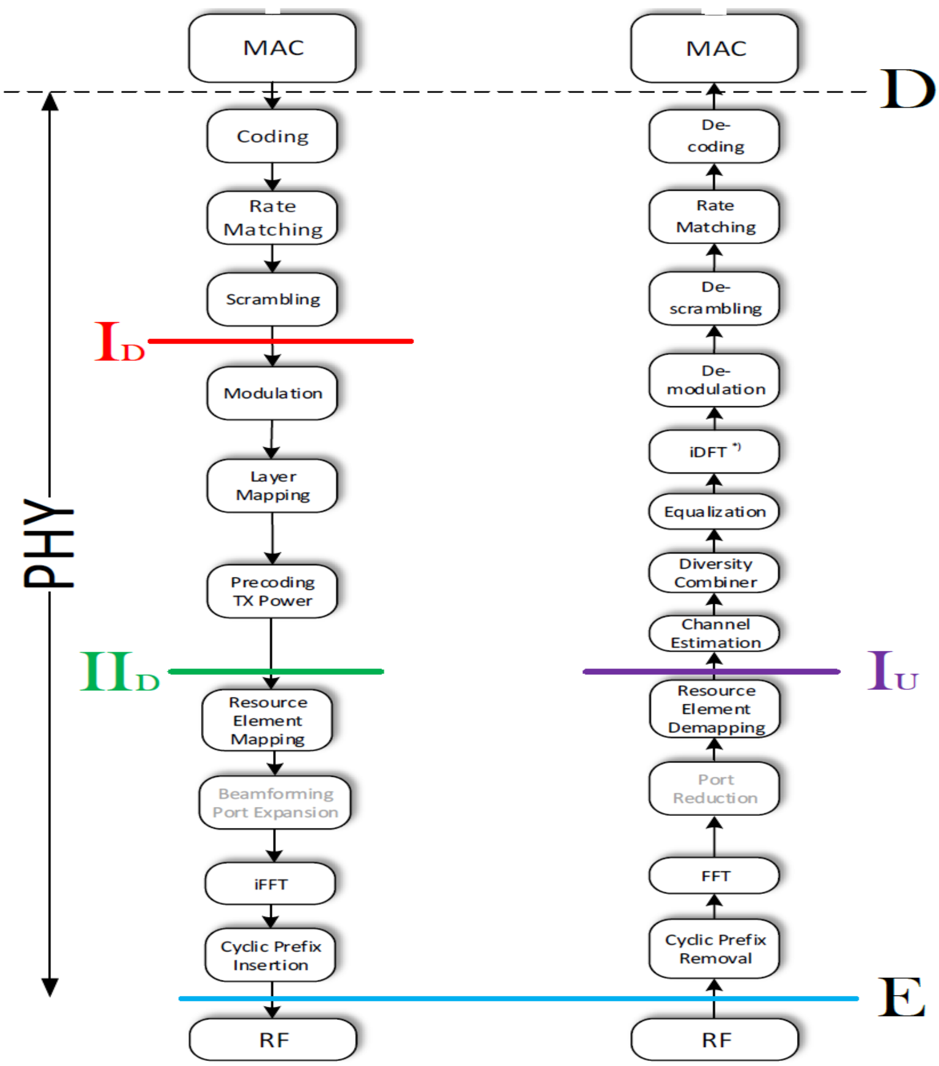

Figure 16. Functional splits [10].

radio unit provided RF processing and analog conversion tasks without including any higher layer 1 processing. On the other hand eCPRI functional split is much higher than the diagram split II_D and I_D and I_U. In 3GPP specifications, it is referred to this split as options 7-1 7-2a and 7-2. The split has merged some L1 baseband processing to the Radio Unit, which increases the complexity of the RU in both hardware and software. Fortunately, this additional RU complexity does not come without benefit. It typically results in less bandwidth consumption at the fronthaul.

As the split gets closer to the MAC layer, the real-time control exchanged between eREC and eRE increases (as a rule of thumb). On the left side of Figure 16, DL user data processing blocks are illustrated. In case of split (II_D), data will be IQ-oriented ie. Frequency domain data is packetized and transmitted. Where beamforming ports IFFT and cyclic prefix insertion blocks will be moved to the radio unit which will increase bit rate processing . By moving split upwards, bit rate for user plane real-time control data will increase.

4.2.3. ECPRI Message Structure

General structure

As illustrated in Figure 17, the eCPRI message has an ethernet message format. The first 4 bytes are reserved for common headers. Starting from Byte index number 4, payload data will take place. Typically eCPRI transsmision occurs in big-endian fashion. In other words, the most significant byte is transmitted first. The common

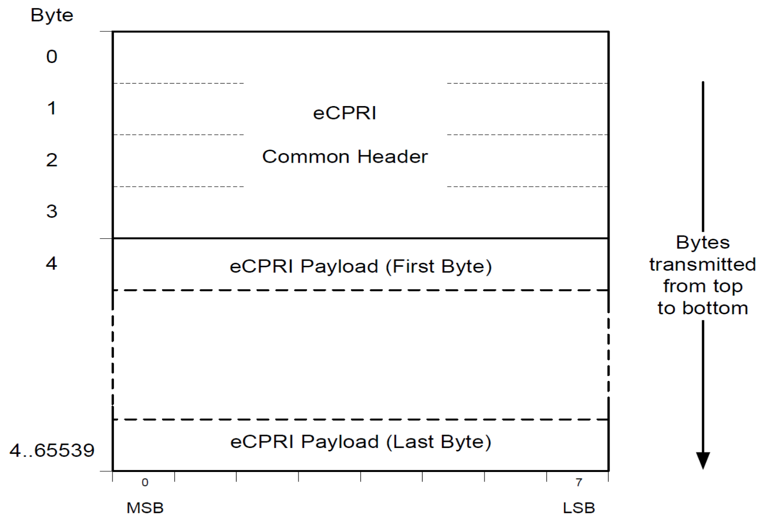

Figure 17. eCPRI message format [10].

header part is divided into 5 fields each one carries specific information . The first byte (byte 0) is spilled as follows:

- The first 4 bits are reserved for eCPRI Protocol Revision. It indicates the eCPRI specification version and it is always a positive number (currently 0001b).
- The 3 next bits are reserved for future changes.
- The least significant bit (LSB), labeled ‘C’ ,is a concatenation indicator . It indicated whether the current message is the last one in eCPRI PDU or not.

The second byte (byte with index 1) represents the message type of the current eCPRI message. The two last bytes (2 and 3) are for eCPRI payload size indication. The maximum supported payload size is 2^{16-1} byte (padding bytes are not included in the size counting). All the previous message data will be encapsulated into a packet associated with the transport network layer header and padding (Figure 17).

As previously mentioned, eCPRI common header contains a specific section for message type. There are 7 known types described in Table 3 .They will be detailed in the next sections.

Table 3: eCPRI Message Types[10]

Message Type #	Name
0	IQ Data
1	Bit Sequence
2	Real-Time Control Data
3	Generic Data Transfer
4	Remote Memory Access
5	One-way Delay Measurement
6	Remote Reset
7	Event Indication
8 - 63	Reserved
64 - 255	Vendor Specific

IQ data message type

The message type is used to transfer IQ data or frequency domain samples between the eREC and eRE. The transmission format is illustrated in Figure 18 which is encapsulated inside the payload part of the eCPRI message. The first two bytes are reserved for physical layer identification, user, layer. Then antenna that has a common property for physical processing (PC_ID). The next two bytes identify each message in a series of IQ data transfer messages, for example OFDM symbol, subcarrier blocks etc. The remaining bytes are reserved for a sequence of IQ sample pairs where I and Q samples are arranged separately. Either the frequency or the time domain sample (depending on the functional split), control information is associated with the message and sent to both nodes in advance. Figure 18 illustrates in detail the transmission of the IQ data message. The first section transmitted is PC_ID ,in order to provide information in advance to the reception node. The series of IQ data will be transmitted section by section for every OFDM symbol period. If the IQ data of each sequence differs in the physical layer of the section, each PC_ID will associate its own IQ sequence data .

ORAN defines the following structure for UL or DL IQ data (Figure 19). The figure shows a split in the IQ samples part, where it is divided into 3 main parts: The U plane message common header (pink) is spitted as followed:

- dataDirection: Base station data direction . 0 for UL and 1 for DL.
- paylod version: version of the payload referring to the specification version, it is set to 0x1 for the specification version v2.00.
- filter index: the index of the channel filter used between the IQ data and the air interface
- frameId: counter for 10ms frames (range 0 to 255).

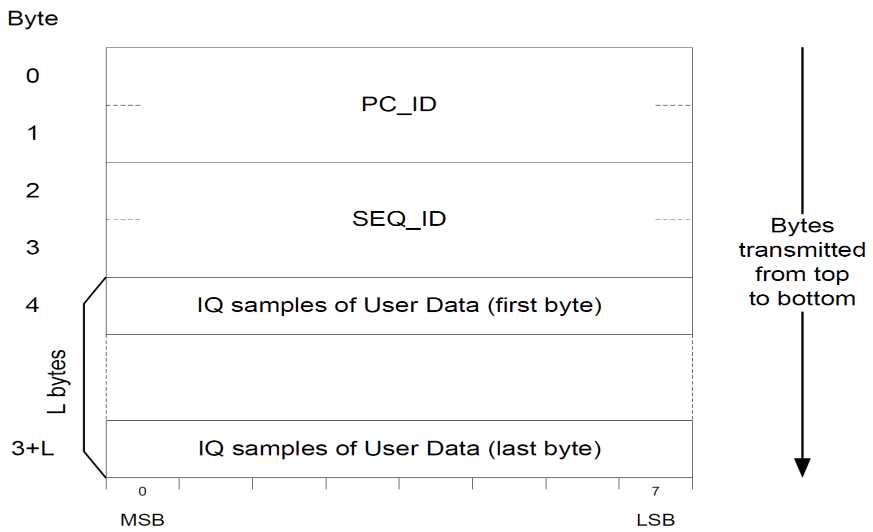

Figure 18. IQ data transfer message format [10].

- subframeId: slot number within a 1ms sub frame (range 0.. Nslot-1, depending on Sub carrier Spacing used).
- SymbolID : identifies a symbol number within a slot (0..13).
- SectionId: data section identifier.
- rb: resource block indicator.
- synmInc: symbol number increment command (0 do not increment / 1 increment).
- start Prbu: index of the starting PRB in a user plane data section.
- numPrbu: number of PRBs in this user data section.
- udCompHdr: describes how data is mapped to the PRB area. (udIqWidth:number of bits in I or Q , udCompMeth: compression method)
- Reserved: one byte reserved for future user.

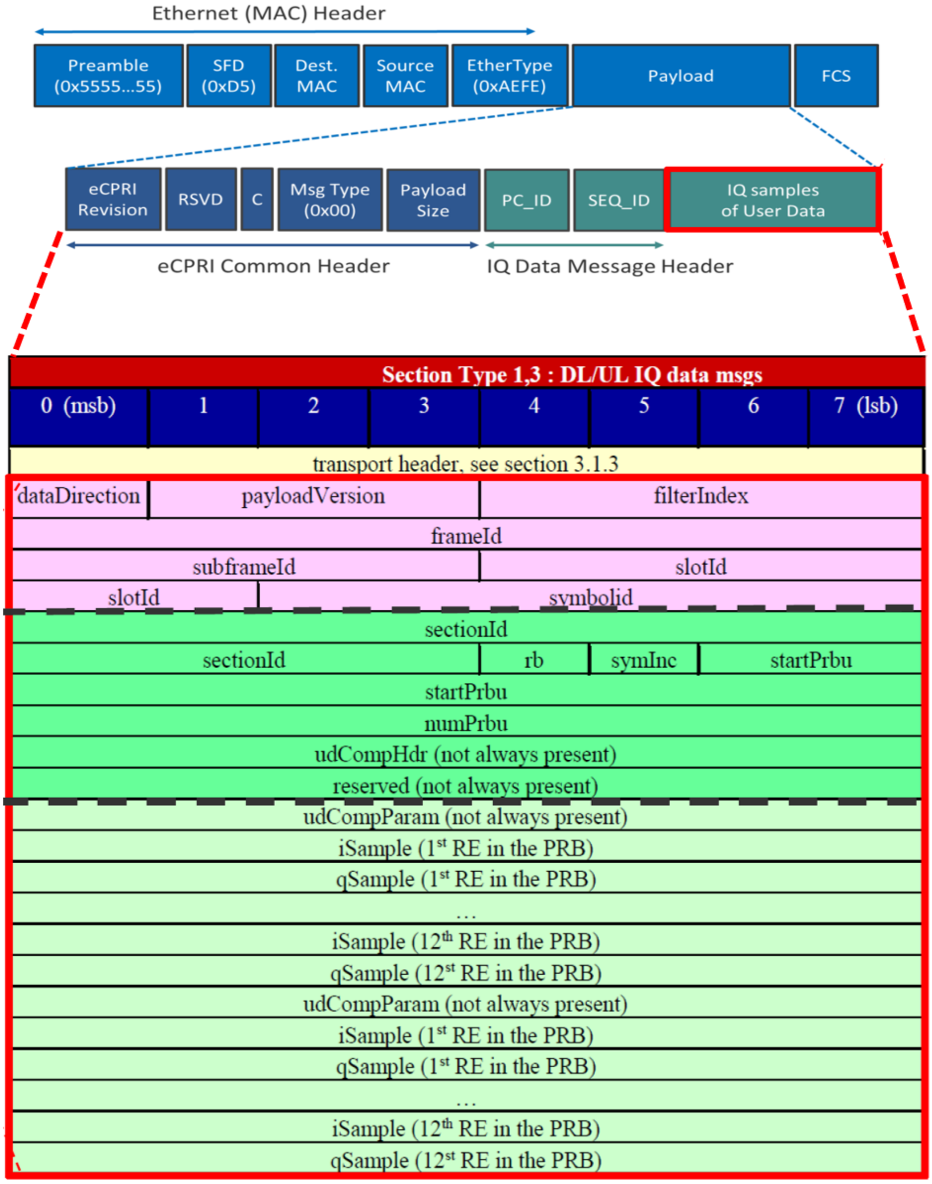

Figure 19. IQ data transfer message ORAN format(adopted from [7]).

Bit Sequence message type

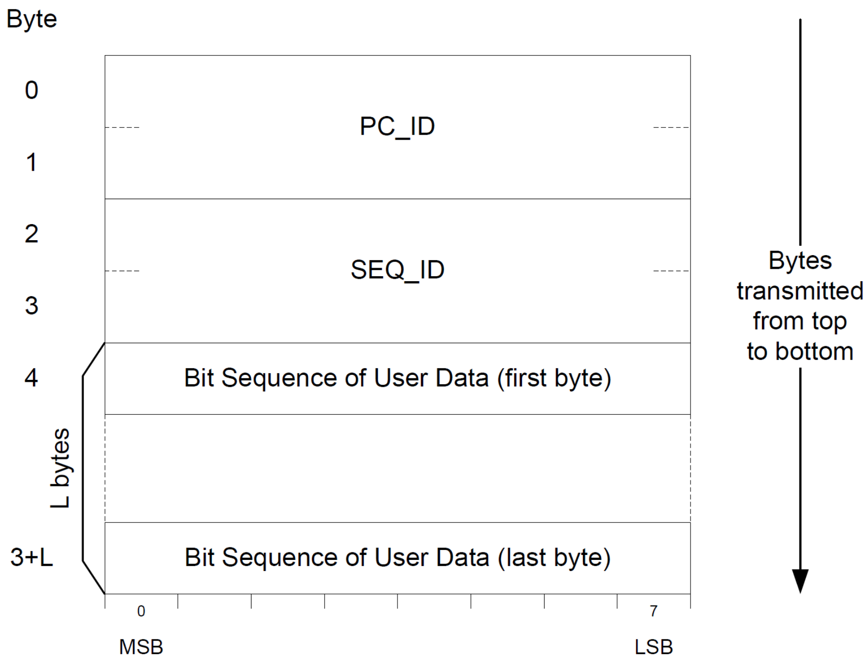

Figure 20. Bit Sequence Transfer messages format [10].

Bit sequence is a message type used to transfer Bit sequences between the two eCPRI nodes. As shown in Figure 20, the message structure is similar to the IQ message type except that the data transferred is not an IQ sample but a sequence of bits for user data. This data transmission type is used when the channel coded data comes before the modulation mapping. In other words, bit sequence message type is used for split options higher than 7.2. The length of a bit sequence in a message is vendor-specific and can be known by the transmit/ received node in advance. The bit sequence message transfer manner is similar to the IQ message format, where real control information for PC_ID is sent first, and the bit sequence is sent next[10].

Real-Time Control Data message type

A real-time control data message is implemented to ensure real-time data exchange between the two eCPRI nodes. These control messages contain various types of information associated with the user plane data (IQ data or Bit Sequence).
Typically, the control messages are sent before the corresponding user plane to provide

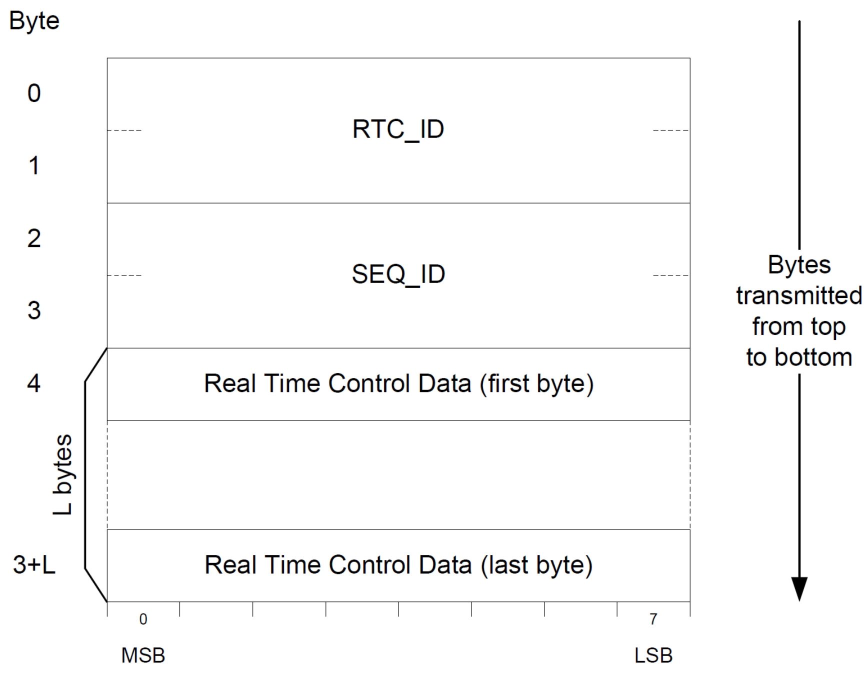

Figure 21. Real-Time Control Data message format [10].

configuration, measurement, and real-time control parameters for the recipient node to be prepared for the next user plane data coming. As illustrated in Figure 21, the Real-time Control Data identifier part (RTC_ID) reserves the first two bytes of the message. It indicates the message structure of specific control, configuration, status, measurement and request, response, and indication type. Byte 2 and 3 are reserved for SEQ_ID where each message in a series of real-time control data messages is identified. The remaining bytes are for Real-time control data which contain the user data that the recipient needs for configuration and User plane reception preparation. Logically, Control data messages are sent prior to the associated user data messages in the form of IQ data or Bit sequence.
ORAN alliance defined several types of control messages. Control plane format differences lie on the type of control function each control plane is assigned for. The control message will carry specific information depending on the section type(see Table 4). Section type 0 for guard band periods, section type 1 for DL and UL control message, section type 3 for PRACH and mixed numerology, section type 5 for UE scheduling information conveyance, section type 6 channel information conveyance, section type 7 LAA message O-DU to O-RU or O-RU to O-DU.

Table 4: Real-Time Control Data message Section Type “0”[7]

<table>
<tr><th colspan="10">Section Type 0 : idle / guard periods</th></tr>
<tr><th>0 (msb)</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7 (lsb)</th><th># of bytes</th><th></th></tr>
<tr><td colspan="8">transport header, see section 3.1.3</td><td>8</td><td>Octet 1</td></tr>
<tr><td>dataDirection</td><td colspan="3">payloadVersion</td><td colspan="4">filterIndex</td><td>1</td><td>Octet 9</td></tr>
<tr><td colspan="8">frameId</td><td>1</td><td>Octet 10</td></tr>
<tr><td colspan="4">subframeId</td><td colspan="4">slotId</td><td>1</td><td>Octet 11</td></tr>
<tr><td colspan="2">slotId</td><td colspan="6">startSymbolid</td><td>1</td><td>Octet 12</td></tr>
<tr><td colspan="8">numberOfsections</td><td>1</td><td>Octet 13</td></tr>
<tr><td colspan="8">sectionType = 0</td><td>1</td><td>Octet 14</td></tr>
<tr><td colspan="8">timeOffset</td><td>2</td><td>Octet 15</td></tr>
<tr><td colspan="8">frameStructure</td><td>1</td><td>Octet 17</td></tr>
<tr><td colspan="8">cpLength</td><td>2</td><td>Octet 18</td></tr>
<tr><td colspan="8">Reserved</td><td>1</td><td>Octet 20</td></tr>
<tr><td colspan="8">sectionId</td><td>1</td><td>Octet 21</td></tr>
<tr><td colspan="4">sectionId</td><td>rb</td><td>symInc</td><td colspan="2">startPrbc</td><td>1</td><td>Octet 22</td></tr>
<tr><td colspan="8">startPrbc</td><td>1</td><td>Octet 23</td></tr>
<tr><td colspan="8">numPrbc</td><td>1</td><td>Octet 24</td></tr>
<tr><td colspan="8">reMask[11:4]</td><td>1</td><td>Octet 25</td></tr>
<tr><td colspan="4">reMask[3:0]</td><td colspan="4">numSymbol</td><td>1</td><td>Octet 26</td></tr>
<tr><td>ef</td><td colspan="7">reserved (7 bits)</td><td>1</td><td>Octet 27</td></tr>
<tr><td colspan="8">reserved (8 bits)</td><td>1</td><td>Octet 28</td></tr>
<tr><td colspan="8">section extensions as indicated by”ef” if any</td><td>var</td><td>Octet 29</td></tr>
<tr><td colspan="8">...</td><td></td><td></td></tr>
<tr><td colspan="8">sectionId</td><td>1</td><td>Octet N</td></tr>
<tr><td colspan="4">sectionId</td><td>rb</td><td>symInc</td><td colspan="2">startPrbc</td><td>1</td><td>N+1</td></tr>
<tr><td colspan="8">startPrbc</td><td>1</td><td>N+2</td></tr>
<tr><td colspan="8">numPrbc</td><td>1</td><td>N+3</td></tr>
<tr><td colspan="8">reMask[11:4]</td><td>1</td><td>N+4</td></tr>
<tr><td colspan="4">reMask[3:0]</td><td colspan="4">numSymbol</td><td>1</td><td>N+5</td></tr>
<tr><td>ef</td><td colspan="7">reserved (7 bits)</td><td>1</td><td>N+6</td></tr>
<tr><td colspan="8">reserved (8 bits)</td><td>1</td><td>N+7</td></tr>
<tr><td colspan="8">section extensions as indicated by”ef” if any</td><td>var</td><td>N+8</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>Octet M</td></tr>
</table>

Generic Data Transfer

The generic data message type is providing extended data synchronization support when a series of user plane data or control plane data are transferred. For example, generic data transfer messages are transmitted each OFDM symbol period or each message has a unique (SEQ_ID).

Figure 22 shows a generic message structure. PC_ID part (4 bytes) identifies the series characteristics like physical channel, user layer, antenna port,..etc. Next 4 bytes identifies message sequences including OFDM symbols, a block of sub carriers,. . . etc. The Data transferred represents a sequence of either user data samples or control information. The sample size, number of samples, and samples format are vendor-specific [10].

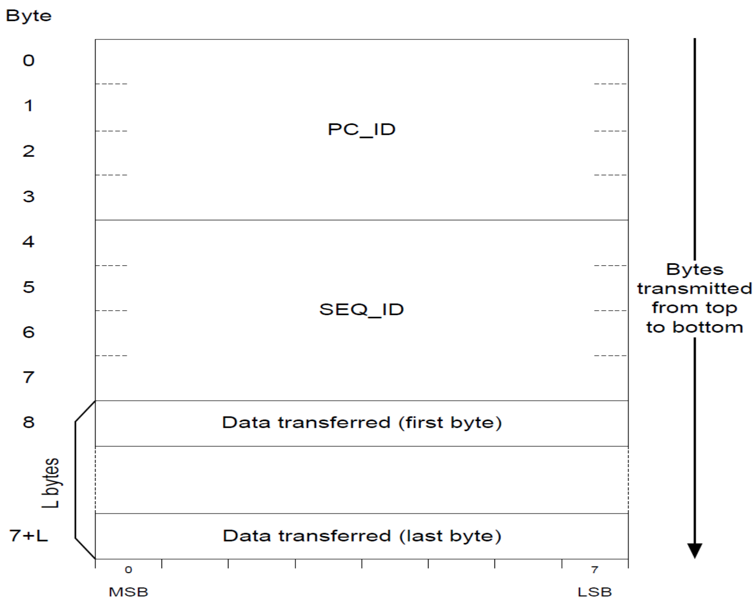

Figure 22. Generic Data Transfer message format [10].

One-Way Delay Measurement message type

A one-way delay measurement message type is used to measure the time delay between eREC and eRE nodes. This measurement is done for several reasons, one of which is synchronization. The process(see Figure 23) begins by sending the master node current time t_1 plus compensation value $\mathrm{t}_{\mathrm{CV1}}$. The receiver time stamps the received message as t_2 and sends it together with compensation value $\mathrm{t}_{\mathrm{CV2}}$. The first sender will calculate the time delay using Equation 1.

$$t_D = (\mathrm{t}_2 - \mathrm{t}_{\mathrm{CV2}}) - (\mathrm{t}_1 + \mathrm{t}_{\mathrm{CV1}}), \tag{1}$$

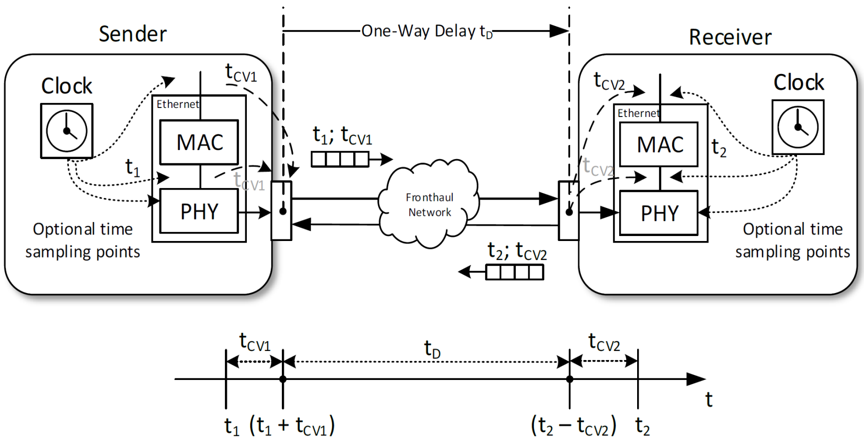

Figure 23. One-way delay measurement concept [10].

This massage procedure can be done frequently with different manners, all specified by the vendor. This message exchange between both eCPRI nodes is specified by the format illustrated in the Figure 24.

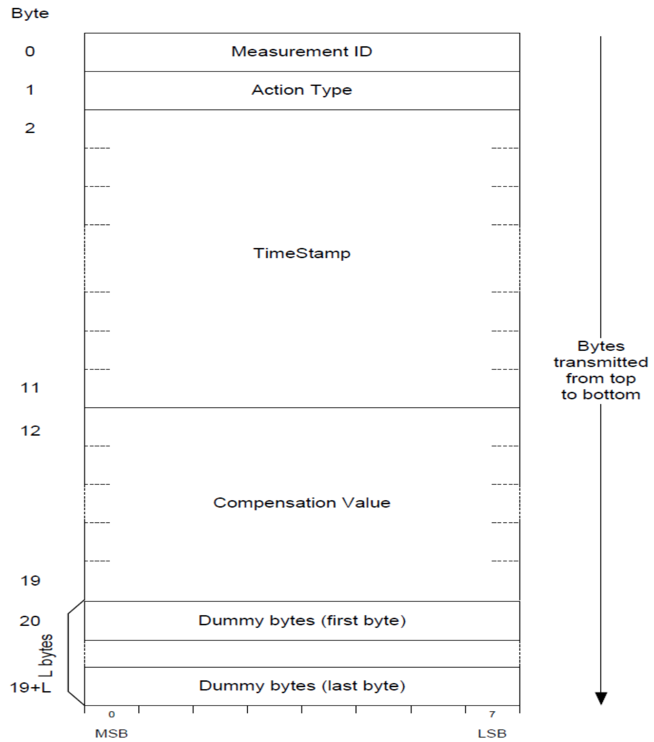

Figure 24. One-way delay measurement message [10].

The first byte for measurement ID used to distinguish between different measurements procedures. This ID is set by the first sender and it will be copied in the second message where node 2 will send it back to node 1. The action byte value describes the action of each message that has been exchanged between the two nodes. It includes the following actions: one way delay measurement direction node 1 to node 2 .

In the inverse direction remote request action 0x03 is encoded in the first message node two to be sent to node one . Time Stamp data differs from one message to another depending on the action of this last one. The time stamp is filled with t_1 in the request message. For the message action the response time stamp is equal to t_2. In the follow-up messages, the time stamp is set to t_1 $+t_{cv1}$. The time stamp part is filled with 0 bits for the remaining message action types. Compensation value is filled with the compensation type measured in nanosecond multiplied by 2^{16} only in three action types: request, response, and follow up .
Dummy bytes: these bytes are used to adapt the delay between the two eCPRI nodes in case of asymmetrical cable lengths connected[10].

5. ECPRI SYNCHRONIZATION AND TIMING

5.1. ECPRI Delay Management

5.1.1. Timing Synchronization Concept

In the eCPRI network all, nodes should be synchronized in different domains: frequency, time, and phase domain. Timing synchronization is required so that all nodes would be aligned to the same common time reference, known as the GM Both eRE and eREC should fulfill requirements set by 3GPP related to timing accuracy at the edge of the fronthaul network. Indeed, eREC is relaxed compared to eRE which requires a high-quality frequency synchronization. However, eREC has to send data to eRE at the correct time, so that it will be enough to process the data and transmit it through the air interface, as well as buffer handling due to network latency variation.

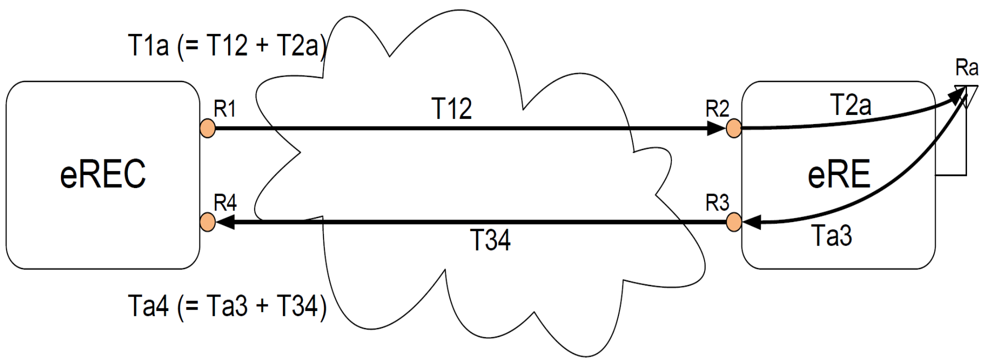

Figure 25. Definition of reference points for delay management[7].

Typically, eREC and eRE are connected in the eCPRI based network as shown in Figure 25. The reference point for timing management is always related to the input and output port of each node. For all fronthaul technology, the timing parameters are common. T12 represents the time delay caused by the medium or the fiber that links the output of eREC and eRE. T2a is the time delay to process the data by eRE and transfer it over the antenna Ra. Ta3 delay is for processing data coming from the antenna and transmitted to port 3. T34 is transport network delay of user data packets between the Rx output of the eRE and input of eREC. Finally, T1a is the total time delay of user data starting from the eREC input port 1 until transmitting the IQ data over the eRE antenna. Same for Ta4 but in the opposite direction where the data flow comes from antenna ends to R4 eREC input port.

5.1.2. Delay Management Downlink Direction

After synchronization of the two eCPRI nodes, DL and UL, data transmission starts. Since different transmission methods exist in eCPRI, some amount of time is always required to transfer packets of data from eREC and eRE. As the IQ data transmitted over eCPRI is in the frequency domain, the symbol duration affect directly the amount of time needed for packet transmission. In other words, all bandwidth, amount of data compression, and eRE data rate can affect the transmission time.

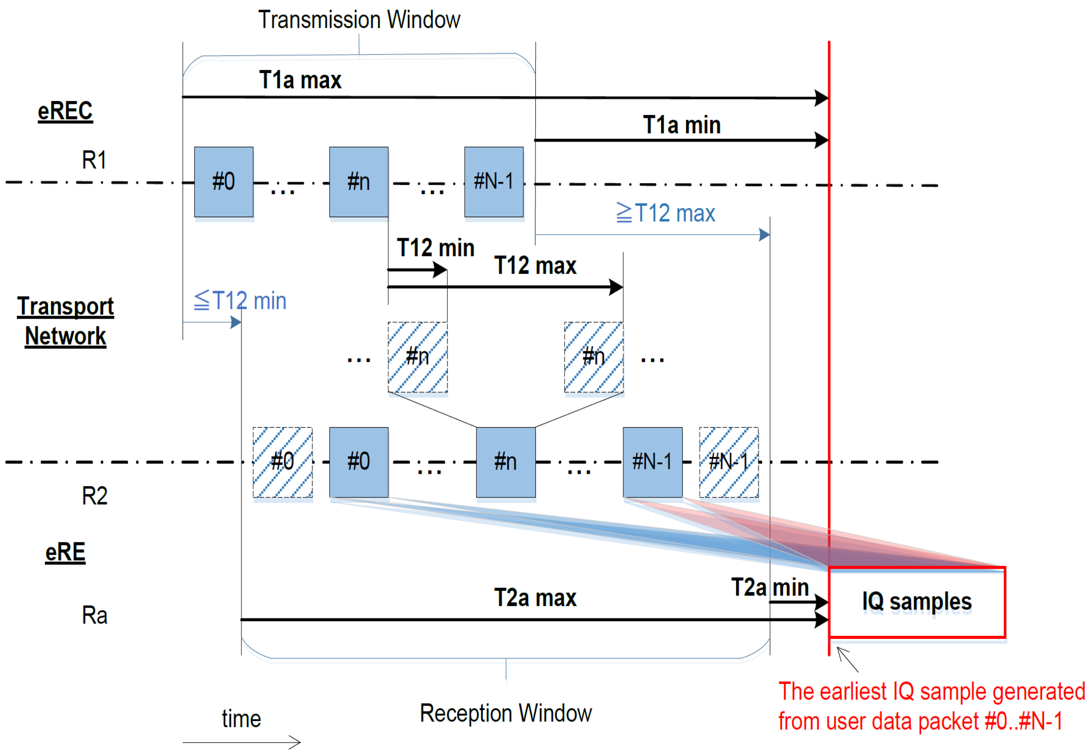

Figure 26. Timing relations in DL direction[10].

In the downlink direction, the following timing parameters are present : T12 transport network delay between port 1 and port 2. T12 can vary in an interval named transport variation 4. It is bounded with T12 min and T12 max. T12 min is the minimum delay of the fastest path data can take to link the two eCPRI nodes. T12 max is the maximum end to end one-way delay. So the User data will take a delay T12 such that :

$$\mathrm{T12min} < \mathrm{T12} < \mathrm{T12max} \tag{2}$$

Once the data reaches the RU where it should be processed, T2a is the timing difference between the reception of user packets from Radio module Tx input port 2 to the transmission of IQ samples at the antenna port (a). to compensate the different T12 values, the Radio module is capable of buffering data, which implies that the T2a timing values change depending on which path the user data took to reach port number 2. Usually T2a min is the minimum timing for the Radio module to process the data and T2a = T2a min when T12 is big enough. It is worth emphasizing that , the worst transmission case in this particular situation is when the data is processed exactly at its time of arrival to port 2. Besides, in T2a max case Radio module is on its maximum buffering capability. This means whenever the data arrives earlier it will be buffered until T2a min to start processing. Generally when T12 is minimum, data will arrive early enough to be buffered in the Radio module buffer. If the packets arrive outside the windows defined above, it will not be processed. T1a is the sum of both T12 and T2a. It covers all the timing delays starting from eREC output port (1) to eRE antenna port. T1a max is the maximum delay user data can take from port 1 to antenna. In this case T12 is less or equal to T12min value and T2a is equal to T2a max. where T1a min is the best or minimum time delay in which T12 = T12 max and T2a = T2a min [10]. The concept is resumed in the following formulas.

$$\text{Transmission window} = \text{T1amax} - \text{T1amin} \tag{3}$$

$$\text{Reception window} = \text{T2amax} - \text{T2amin} \tag{4}$$

5.1.3. Delay Management Uplink Direction

After the Downlink phase. Uplink transmission can start, the IQ data are fed to the eRE Antenna port. This data will be processed by the eRE. Then they will be encapsulated and transmitted over packets from the Rx port number 3.

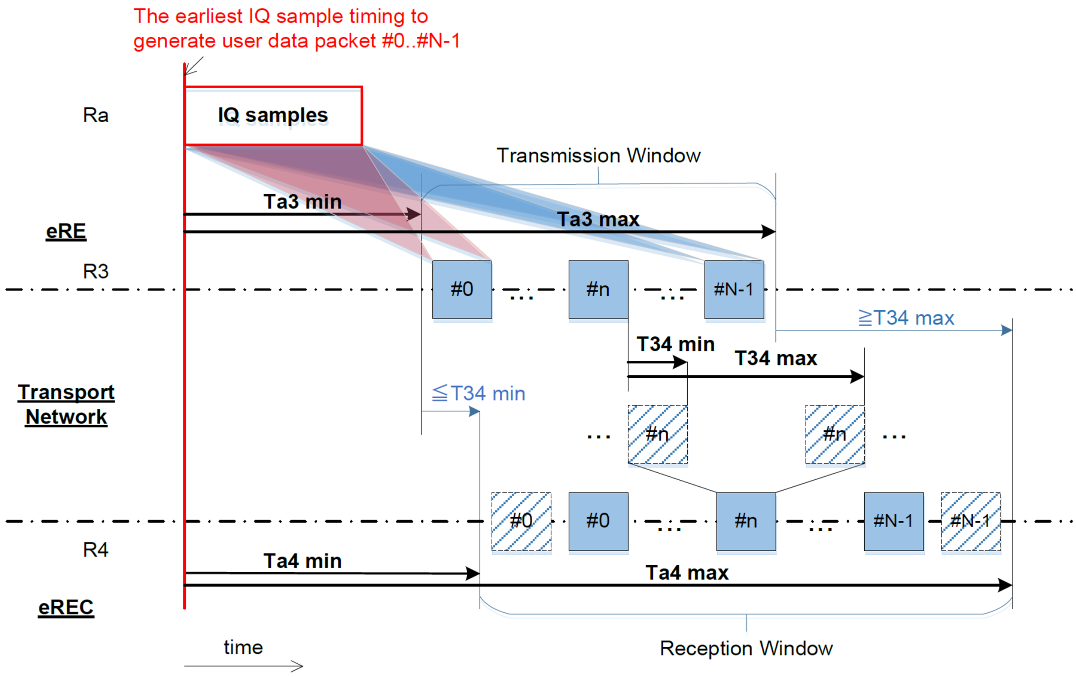

Figure 27. Timing relations in UL direction[10].

The timing difference between the reception of the IQ sample and the start of the transmission of the packet at port 3 is Ta3. Similar to the DL scenario, Ta3 can vary based on the buffering time of the Radio module. Ta3 min is the minimum time Radio Unit process then send the IQ samples; it can be . Ta3 max is the maximum buffering time of eRE in a way that the IQ sample packets will be buffered inside the radio before starting its transmission to eREC. Next packets are transmitted from Rx port number 3 to port number 4 in eREC spending a delay of T34, which is the same as T12 but in the opposite direction. T34 max is the maximum end to end time delay where T34 min is the shortest . Finally, Ta4 is the time delay between the reception of the first IQ sample on the eRE antenna and the input eREC port number 4. Ta4 min represents the minimum time delay scenario where the eRE buffering is near to zero and T34 is minimum. Furthermore, Ta4 max can occur when the Radio module is at maximum buffering and T34 is near or equal to T34 max.

If packets arrive late or earlier enough to be out from one of the windows described by Equations 5 and 6, then the packets will be thrown out.

$$\text{Uplink transmission window} = \text{Ta3max} - \text{Ta3min} \tag{5}$$

$$\text{Uplink reception window} = \text{T4amax} - \text{T4amin}, \tag{6}$$

5.2. ORAN Fronthaul Timing and Synchronization

5.2.1. Transmission and Reception Window in ORAN

As discussed in the Chapter 3, one of the most important features of the ORAN is its openness. This last has brought a variation on the fronthaul interface timing. The communication between O-DU and O-RU is delayed by an amount of time T12 in the downlink, and T34 in the uplink. Unlike previous fronthaul technology transmission, the delay between the two nodes may not be constant due to a switching delay, known as packet delay variation (PDV). The delay is tolerable in a range where the maximum and minimum value is set (T12min and T12max for downlink then T34 min and T34 max for uplink).

ORAN franthaul owns a special transmission nature where the sender takes an

Table 5: ORAN timing parameters (adopted from [7])

Direction	Node	Time parameter	Latency	eCPRI	
				Minimum	Maximum
Downlink	O-DU	T1a	Measured from output at O-DU (R1) to transmission over the air.	T1amin	T1amax
	O-RU	T2a	Measured from reception at O-RU (R2) to transmission over the air	T2amin	T2amax
Uplink	O-DU	Ta4	Measured from reception at O-RU antenna to reception at O-DU port (R4).	Ta4min	Ta4max
	O-RU	Ta3	Measured from reception at O-RU antenna to output at O-RU port (R3)	Ta3min	Ta3max

amount of time to transmit packet data. This kind of transmission forces the receiver to buffer the packets where symbol data is encapsulated. However, the time of buffering may vary as the duration of the symbol is sensitive to several parameters including subcarrier spacing configuration. For this reason a window is defined to bound this buffering time and the time of data transmission between the two nodes. In downlink, the transmission window is set by the O-DU based on O-RU buffering characteristics.The position (in time) of the reception/ transmission windows at the O-RU is fixed relative to the air interface. The window boundaries are T1amax and T1amin only between those two points the O-DU can send the packets. Therefore, the transmission window size is defined by T1amax- T1amin. The O-RU is the recipient in downlink, so the radio unit will buffer the packets arriving from O-DU within the reception window. The timing parameters of the reception window are: T2amax as the earliest time when the radio starts buffering the data packets, the packets will be then buffered until T2amin. T2amin which represents the minimum time a packet needs to reach the O-RU , after that time all received packets will be discarded. Typically, T2amin is defined as the time when the radio will immediately start processing the arrived (or buffered) packets. In other words the buffering capability of O-RU is T2max-T2Amin which is the size of the Reception window.

In uplink direction the transmission window is within the O-RU. This window will handle the packet of specific symbols before starting their transmission. The transmission window boundaries are Ta3min as the earliest time to transmit the packet to O-DU while Ta3max marks the end of the transmission. The packets will be delayed by variable time values variate in the interval T34min and T34max. In all cases, the reception window (in O-DU) should accept the arrived packets. The reception window is defined by Ta4max and Ta4min, and its size is T4amax-T4amin.

In both cases O-DU should design the transmission window (in Downlink) and the reception window (in uplink) to be large enough so that all transmitted packets would arrive within the reception window. For the design of the window, O-DU needs both O-RU Delay Characteristics (T2a min T2a max for Downlink, and Ta3min and Ta3 max for uplink) and the transport Network Delay characteristics (T12min T12max in the downlink direction and T34 min and T34 max for uplink). As shown in the Table 5, T1amax should be less than T2amax + T12min (earliest scenario) i.e late enough. This condition will ensure that the packets sent from O-DU will not arrive before T2amax. The right boundary of this transmission window T1amin should be set greater than T2amin+T12max, i.e early enough to ensure packets are received before processing start-time of O-RU T2amin. In the uplink direction, O-DU aligns the reception window so that Ta4min should be less than T3amin+T34min, which means the fastest path to get packets received, i.e early enough to be able to receive starting from the earliest possible moment when the packet can arrive. While T4amax should be bigger than Ta3max + T34max i.e late enough to ensure all the packets are received even in the worst case where packets are late.

As mentioned at the beginning, all the window alignment and configuration is based on O-RU delay characteristics. The parameters should be reported with an accuracy of 200 ns.

5.2.2. ORAN Downlink Timing Measurement

As already discussed in Chapter 3, the ORAN fronthaul interface is divided into C plane and U plane. The C plane contains the configurations to prepare the O-RU for U plane processing. For this reason, the ORAN interface indicated that the C plane should arrive in advance of the corresponding U plane by Tcp_adv_dl . The C plane window is identical to U plane one but shifted left by time parameter Tcp_adv_dl, i.e they have the same size.

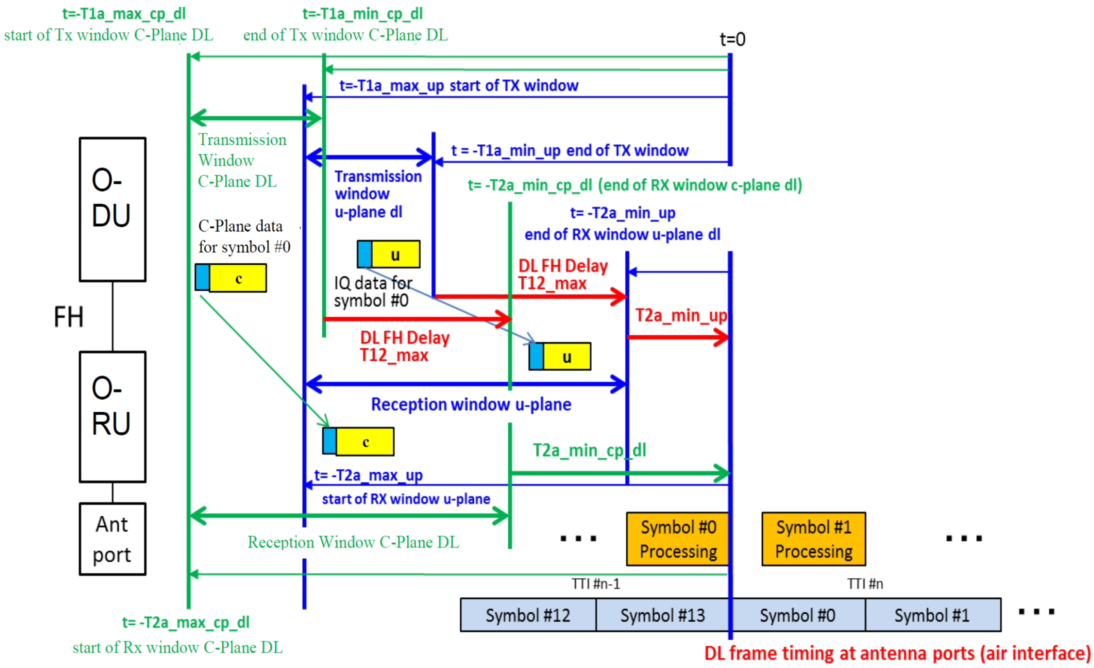

Figure 28. Timing relations per symbol IQ in DL direction [7].

Table 6: Downlink delay relationship (adopted from [7])

	Earliest transmission from O-DU	**Latest Transmission from O-DU**
U-Plane	**T1a_max_up ≤ T2a_max_up + T12_min**	**T1a_min_up ≥ T2a_min_up + T12_max**
C-Plane	**T1a_max_cp_dl ≤ T2a_max_cp_dl + T12_min**	**T1a_min_cp_dl ≥ T2a_min_cp_dl + T12_max**

Figure 28 illustrates symbol 0 processing in detail, starting from ODU ending by Air interface t =0. The downlink transmission starts sending the C plane in advance (green path). As known, t=0 is the time when Symbol number air interface transmission starts.O-DU Transmission window for C plane starts at t=-T2a_max_cp_dl. This time value is the earliest case when the O-DU starts transmitting the C plane packet (start of Tx window Cp-dl) the End of TX C plane widow is characterized byt = −T1a_min_cp_dl, at this time no packet of the specific symbol (ex symbol 0) will be sent because it risks to be received late then outside the reception window of O-RU.

The C plane packets will be delayed by transmission delay between node 1 and 2. The transmission delay can vary between $\mathrm{T12\_max}$ and $\mathrm{T12\_min}$. In all cases, the Transmission window is designed to transmit the packets at a time interval ensuring their safe arrival to the O-RU reception window. In the C plane case (always focusing on the green path in Figure 28) the Reception window starts at the same time the transmission window does.$\mathrm{T2a\_max\_cp\_dl}$ signifies the earliest time the O-RU accepts C plane packets coming from the O-DU. All packets received after this time and before the end of the reception window will be buffered waiting for the O-RU processing start. $\mathrm{T2a\_min\_cp\_dl}$ defines the end of the reception window where no control packets will be accepted after that time. Simultaneously, it is the moment when O-RU starts processing the C plane packets. The C plane data will set specific parameters and update module configuration so that O-RU will be prepared to process the coming U plane packets of symbol number 0.

Focusing on the blue path in Figure 28 with the same concept of C plane procedure, the O-DU transmission window will send the packet no earlier than $\mathrm{T1a\_max\_up}$ (start of Tx window). $\mathrm{T1a\_min\_up}$ signifies the end of transmission Window so no U plane packet will be sent after this time. similar to C plane, U plane packets will be delayed by a fronthaul delay defined in the interval $\mathrm{T12\_max}$ and $\mathrm{T12\_min}$. Whatever the fronthaul path taken, U plane packets will arrive within the reception window. O-RU reception window starts at $\mathrm{T2a\_max\_up}$ when the earliest packets can be accepted. Packets are buffered until O-RU processing time begins. At that time $(\mathrm{T2a\_min\_up})$ no U plane packet is accepted.

To ensure proper transmission and reception in the Network, the following criteria are defined to be followed whenever the Windows are designed by O-DU.

- O-RU reception window range > O-DU transmission window + FH DL transport [7]

Table 7: U-Plane DL delay boundaries (adopted from [7])

Downlink	Method
T1a_max_up	≤ T12_min + T2a_max_up
T1a_min_up	≥ T12_max + T2a_min_up
T2a_max_up	≥ T2a_min_up + (T12_max – T12_min) + O-DU Transmission Window
T2a_min_up	Specified per Use Case
T12_max	Specified per Use Case
T12_min	Specified per Use Case
O-DU Transmission Window	Specified per Use Case

This means that O -RU reception window must be the largest window and larger than the addition of the transmission window and transport time variability window (see Table 7).

In conclusion,$\mathrm{T12\_min}$ should be determined to be the shortest transmission path based on network configuration (fiber delay in addition to switching delay). In addition, the longest fiber and switching, delays should be presented on the time delay parameter $\mathrm{T12\_max}$. $\mathrm{T2a\_min}$ fixed processing time of the O-RU and $\mathrm{T2a\_max}$

Table 8: C-Plane DL delay boundaries (adopted from [7])

Downlink	Method
Tcp_adv_dl	Specified per Use Case
T1a_max_cp_dl	T1a_max_up + Tcp_adv_dl
T1a_min_cp_dl	T1a_min_up + Tcp_adv_dl
T2a_max_cp_dl	T2a_max_up + Tcp_adv_dl
T2a_min_cp_dl	T2a_min_up + Tcp_adv_dl
T12_max	Same as U-plane DL
T12_min	Same as U-plane DL

the maximum buffering capability of the same node should also be reported with an accuracy of 200 ns as defined in the previous section. Finally, C plane and U Plane transmission period $\mathrm{Tcp\_adv\_dl}$ must be determined to exactly settle C plane transmission and reception window. Table 8 illustrates how the downlink related parameters are further calculated

5.2.3. ORAN Uplink Timing Measurement

For the uplink case illustrated in Figure 29, symblo0 is taken as an example of uplink transmission.

Similarly to DL C plane procedure explained earlier, UL C plane is sent from O-DU to O-RU with the Same rules applied in DL. However, the transmission window and reception window characteristics are different. The C plane transmission window for uplink is defined by its own starting time$\mathrm{T1a_max_cp_ul}$ and ending time at$\mathrm{T1a_min_cp_ul}$. In the same manner, the reception window for C plane uplink starts at$\mathrm{T2a_max_cp_ul}$ ends at $\mathrm{T2a\_min\_cp\_ul}$. The only parameters shared between both downlink and uplink C planes are $\mathrm{T12\_max}$ and $\mathrm{T12\_min}$ as they have the same direction. Focusing on the blue path, t=0 signifies the time when the symbol 0 air interface has been received by O-RU. The Radio starts immediately processing the data. This will impose some delay referred to as $\mathrm{Ta3\_min\_up}$.

Furthermore, $\mathrm{Ta3\_max\_up}$ signs the starting of the transmission window (located in O-RU) which is the earliest time O-RU can send U plane Uplink for a specific symbol. The ending time of the transmission window in uplink direction defines the latest time that O-RU can send U plane data for a specific symbol. As usual the packets will be delayed when coming out from O-RU toward O-DU by Ul fronthaul transport delay defined by $\mathrm{T34\_min}$ for the minimum case and $\mathrm{T34\_max}$ when the maximum delay occurs. The reception window in Uplink takes place in O-DU so that O-DU needs to define its time boundaries in a way so that it can accept all arriving packets from O-RU. The start of the reception window set by $\mathrm{Ta4\_min\_up}$ indicates the earliest time the O-RU can accept the u plane UL data packet. When packets arrive after the beginning

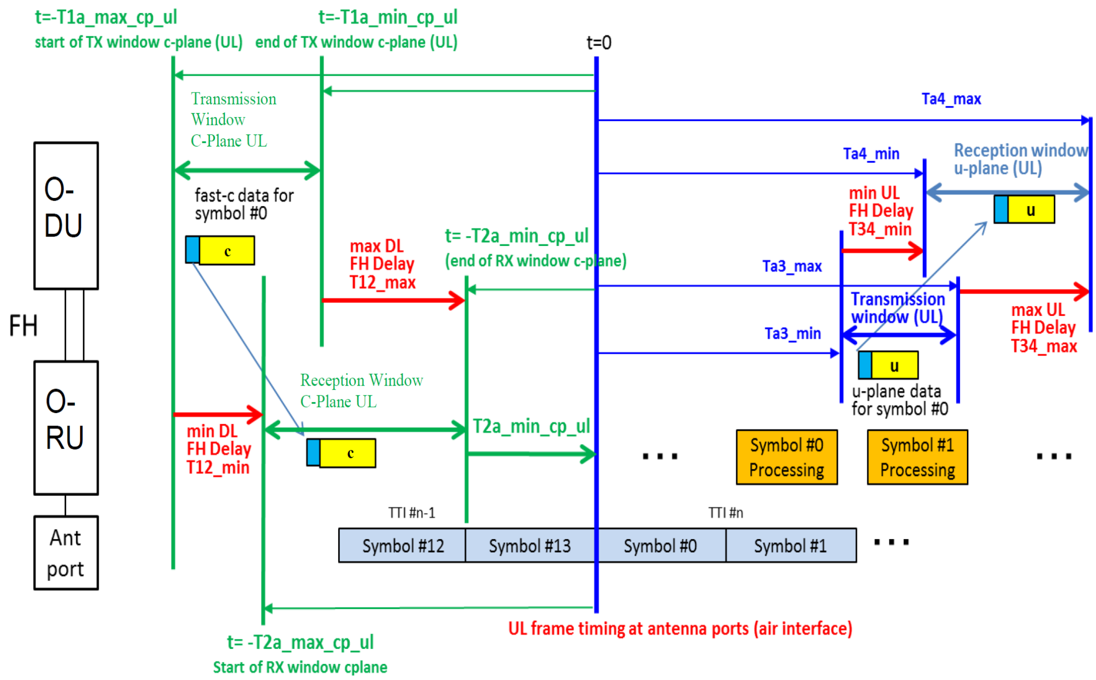

Figure 29. Timing relations per symbol IQ in UL direction [7].

of the reception window, it will be buffered waiting for the O-DU processing to start. The end of this reception window is the last time when O-DU will accept U plane packets. Also it is defined byTa4_max_up which indicates the starting time of data processing in O-DU. To ensure proper transmission and reception in the network the following criteria are defined to be followed when the windows are designed by the O-DU.

- O-RU reception window range > O-DU transmission window + FH UL transport[7]

Table 9: U-Plane Uplink delay boundaries (adopted from [7])

Uplink	Uplink Method
Ta3 max	≤ Ta3_min + O-RU Transmission Window
Ta3 min	Specified per Use Case
Ta4 max	≤ Ta3_max + T34_max
Ta4 min	≥ Ta3_min + T34_min
T34 max	Specified per Use Case
T34 min	Specified per Use Case
O-RU Transmission Window	Specified per Use Case

To conclude, the reception window at O-DU should always be large enough to accept the coming packets from O-DU whenever the transmission case. Similar to downlink direction, the parameters $\mathrm{T34\_mmin}$, $\mathrm{T34\_max}$,$\mathrm{Ta3\_min\_up}$,$\mathrm{Ta3\_max\_up}$, $\mathrm{T2a\_min\_cp\_ul}$, $\mathrm{T2a\_max\_cp\_ul}$, $\mathrm{T12\_max}$, and $\mathrm{T12\_min\_cp\_up}$ should be defined in prior to calculate other parameter and get proper communication between the nodes(see Table 10).

Table 10: C-Plane Uplink delay boundaries (adopted from [7])

Uplink	Uplink Method
T1a_max_cp_ul	**≤ T12_min + T2a_max_cp_ul**
T1a_min_cp_ul	**≥ T12_max + T2a_min_cp_ul**
T2a_max_cp_ul	**≥ T2a_min_cp_ul + (T12_max – T12_min) + O-DU Transmission Window**
T2a_min_cp_ul	**Specified per Use Case**
T12_max	**Specified per Use Case**
T12_min	**Specified per Use Case**
O-DU Transmission Window	**Specified per Use Case**

5.2.4. ORAN Fronthaul Delay Measurement

As discussed in the previous sections, the time delay between the two end points of both the O-RU and the O-DU plays a major role in transmitting and receiving packets between the nodes as well as designing the transmission and the reception windows. Due to the openness of ORAN, the link between the nodes should contain different fiber lengths and switches which increases the possibility of packets taking different paths each time. This interval has been bound by maximum and minimum values. In the downlink direction, $\mathrm{T12\_min}$ represents the shortest path a packet can take, $\mathrm{T12\_max}$ defines the longest path a packet can be transmitted on. Analogously to DL, the UL defines $\mathrm{T34\_min}$ and $\mathrm{T34\_max}$ representing the shortest and longest paths a packet can take, respectively. In order to define the Fronthaul time delay, eCPRI corporation has designed the one-way delay measurement message. The goal of this message is to determine the transport delay as it varies between a maximum and minimum time value that can be estimated as well using a one-way delay message. Figure 30 illustrates the message procedure to define the fronthaul delay. In order to determine T12 O-DU, the measurement is initiated by sending one way delay request to O-RU. This last will respond by a message that contains timestamp t_2 and compensated value to account for the expected delay from the received packet. Next, the O-DU will compute the delay $\mathrm{t_d}$ using the formula indicated in Figure 30. In the Uplink procedure, T34 is defined by the O-DU in a different manner (low part of Figure 30) the O-DU would first send a remote request to O-RU demanding one-way delay measurement. The same downlink procedure is followed to calculate $\mathrm{t_d}$ or T34, but the master node here is O-RU. One way delay measurement is performed before sending C/U plane traffic. The measurement is done periodically since packets can experience different delays through the same network. The measured value will be used by O-DU to design the reception and transmission windows as explained before.

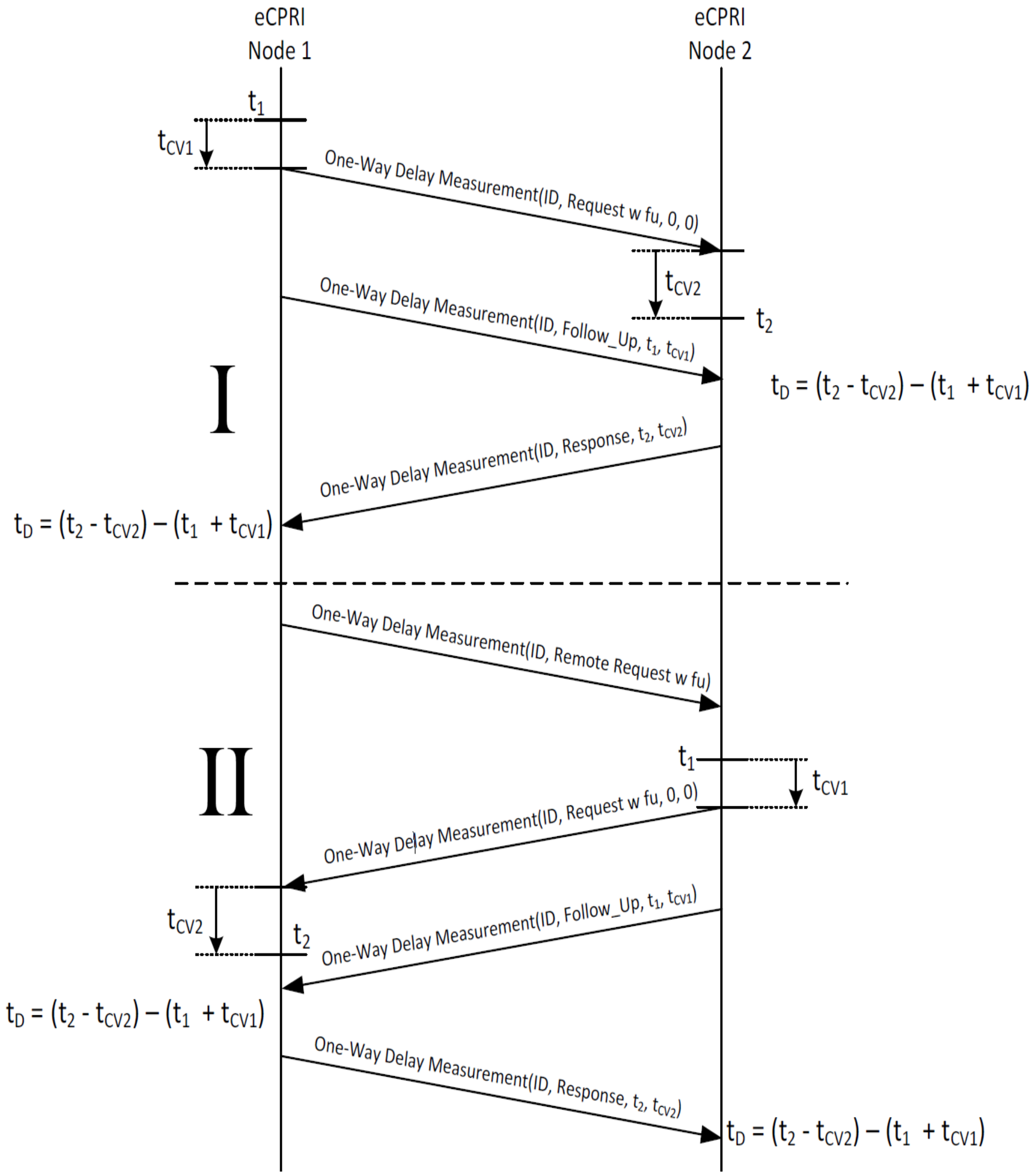

Figure 30. One way delay measurement [10].

6. ECPRI TIMING MEASUREMENT IMPLEMENTATION

The goal of our implementation is to ensure that the transmission/reception window for O-RU are properly aligned to support different networks and nodes communications. Based on ORAN timing specification the test cases would be designed to cover all possibility and to ensure appropriate transmission and reception of packets between O-RU and O-DU. To achieve such objectives a test procedure should be designed along with building of a test environment to execute the testing and verification. The test plan for all packets types of user plane and control plane is based on two presumption.

First of all, sending the packet to be inside the Acceptance window then Expect a normal behavior from Radio unit or correct signal out. Secondly, Assumption is to send the packet outside the acceptance window and expect to have 0 IQ data out. Both assumptions will branch into several test cases built on ORAN Delay management specification. Figure 31 shows high overview on the test plan.

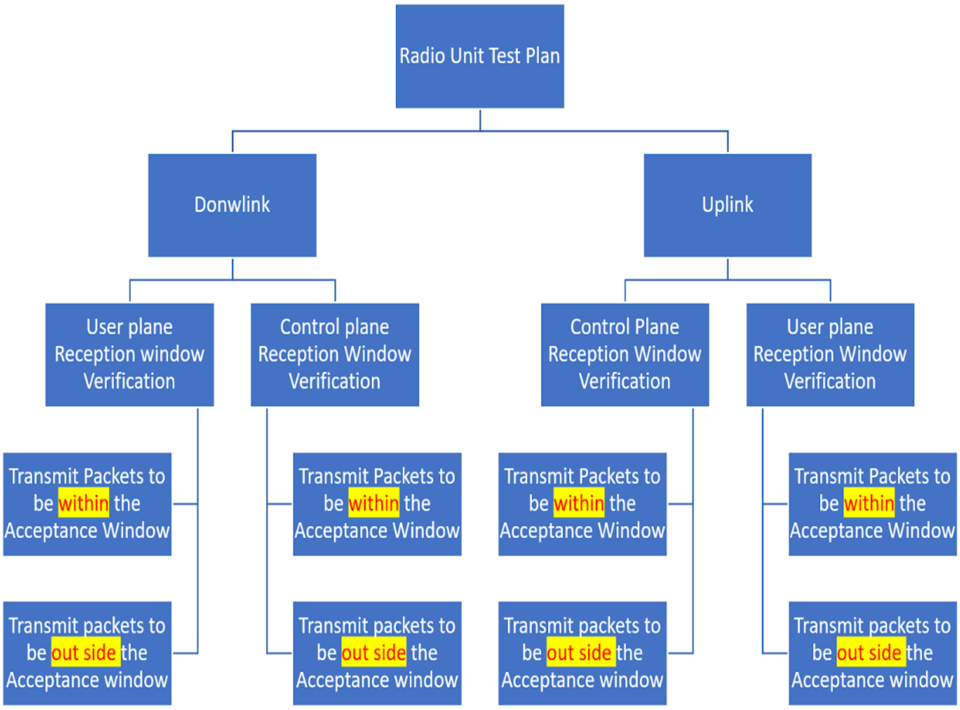

Figure 31. Timing Test Plan.

6.1. ECPRI Timing Downlink Test Cases

In all test cases a test setup should be built with specific hardware to execute the tests and analyse the results . For different downlink test cases , one test setup enough . The Downlink test setup is build to focus better on data flow in downlink direction .

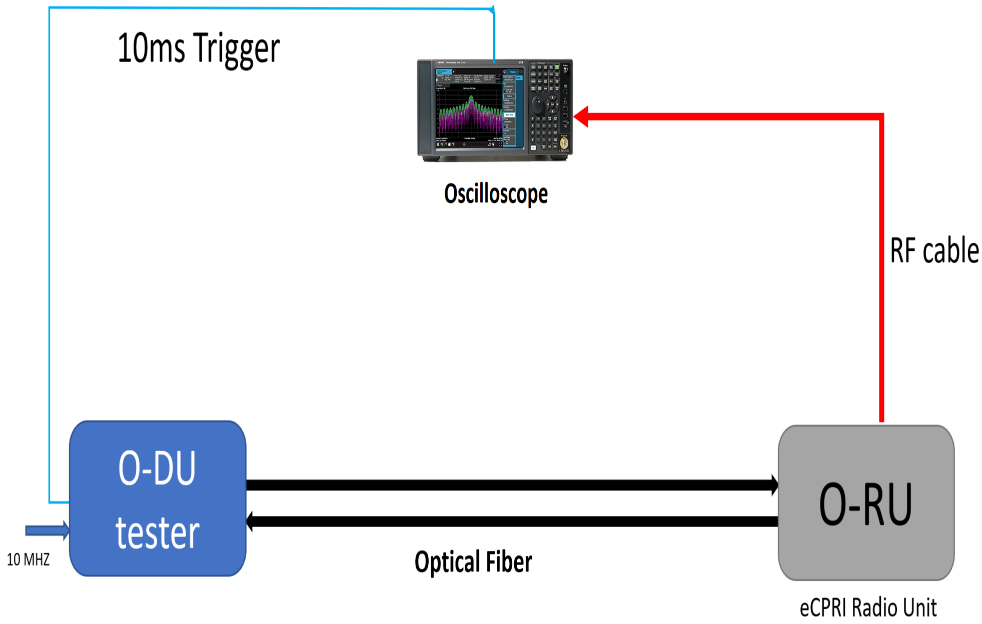

Figure 32. Downlink Test setup.

In the Test setup Figure 32 O-DU tester and O-RU node are connected over an optical fiber with a fixed length this implies that the fronthaul delay is constant in our environment.

From O-RU antenna, RF cable is connected to a signal analyzer or oscilloscope to analyze and decode the air interface signal coming out from Radio antenna. A 10 ms trigger is attached to Signal analyzer to synchronize with the reference transmission time T=0 which represent the Air interface transmission start at Radio Unit Antenna port. Both O-RU and O-DU should be synchronized before starting any transmission . Furthermore One way delay measurement message should report the T12 value prior to any C/U plane traffic.

6.1.1. Downlink User Plane Test Cases

User plane traffic in downlink direction should be received within the radio reception window defined by $\mathrm{T2a\_min\_up}$ and $\mathrm{T2a\_max\_up}$. In this case a correct IQ data is expected to be out as air interface Signal. In Phase 1 Figure 33 of user plane timing test case the goal in to send packets at different timing points, where we should get a correct IQ data as output with acceptable Error Vector Magnitude (EVM). In phase 2, it is the inverse we send the packets outside the reception widow from both sides and also at the boundaries. So that we stimulate the radio unit to through our the packets and wrong data is out from the antenna. The most important thing in those test cases is to fix the Control plane packets transmission to guarantee that they are always received correctly. The O-RU phases test cases branch are illustrated in Figure 33. Each test case will be detailed in the next sections.

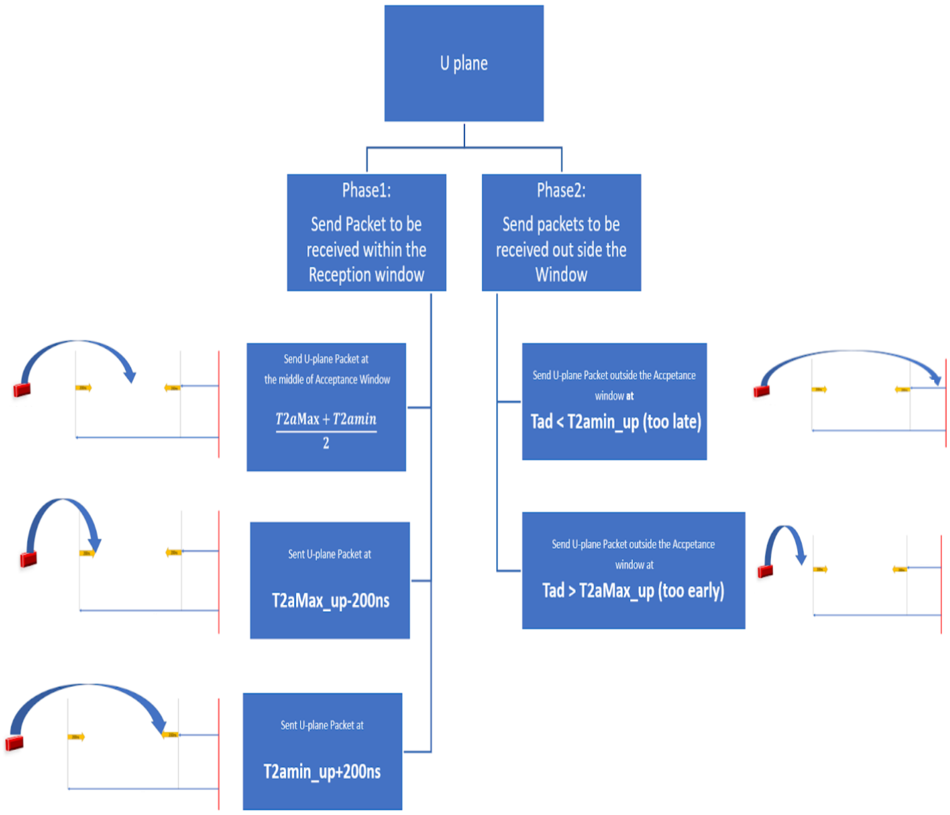

Figure 33. Downlink User plane test plan.

Phase 1 User plane Timing test Cases

a) Send User plane packets at the middle of Reception window

In this test case, O-DU tester should be configured in such a way User plane packets are received exactly at the middle of O-RU reception window. At the same time, C plane packets should be transmitted to be at the middle of their Reception window. As mentioned in the previous chapter, C plane window is characterized by $\mathrm{Tcp\_adv\_dl}$

which is the shift in time of the user plane window. In another word $\mathrm{Tcp\_adv\_dl}$ will exactly define the C plane reception window in addition to $\mathrm{T2a\_min\_up}$ and $\mathrm{T2a\_max\_up}$. In All test cases $\mathrm{Tcp\_adv\_dl}$ is fixed. Figure 34 illustrates user plane packets traffic and C plane packets as well during this test case (symbol 0 processing is an example). $\mathrm{T2a\_min\_up}$ and $\mathrm{T2a\_max\_up}$ are reported by the O-RU T12 delay that is already measured before starting the test and $\mathrm{Tcp\_adv\_dl}$ is also fixed. Using the previous parameter formulas should be set as input for O-DU tester :

$$ODU_{\mathrm{Up\_dl\_adv}} = \frac{\mathrm{T2a\_min\_up} + \mathrm{T2a\_max\_up}}{2} \tag{7}$$

$$ODU_{\mathrm{Cp\_dl\_adv}} = \mathrm{Tcp\_adv\_dl} \tag{8}$$

Equation 38 illustrates the position in time of User Plane data at O-RU. Reception window takes t=0 starting time of air interface transmission as reference (red color). $\mathrm{O-DU\_Cp\_DL\_adv}$ represents advance time between $\mathrm{ODU}_{\mathrm{Up\_DL\_adv}}$ and C plane reception time at O-RU. After setting the variable value in the O-DU tester, the transmission starts and the result will be analyzed by signal analyzer .

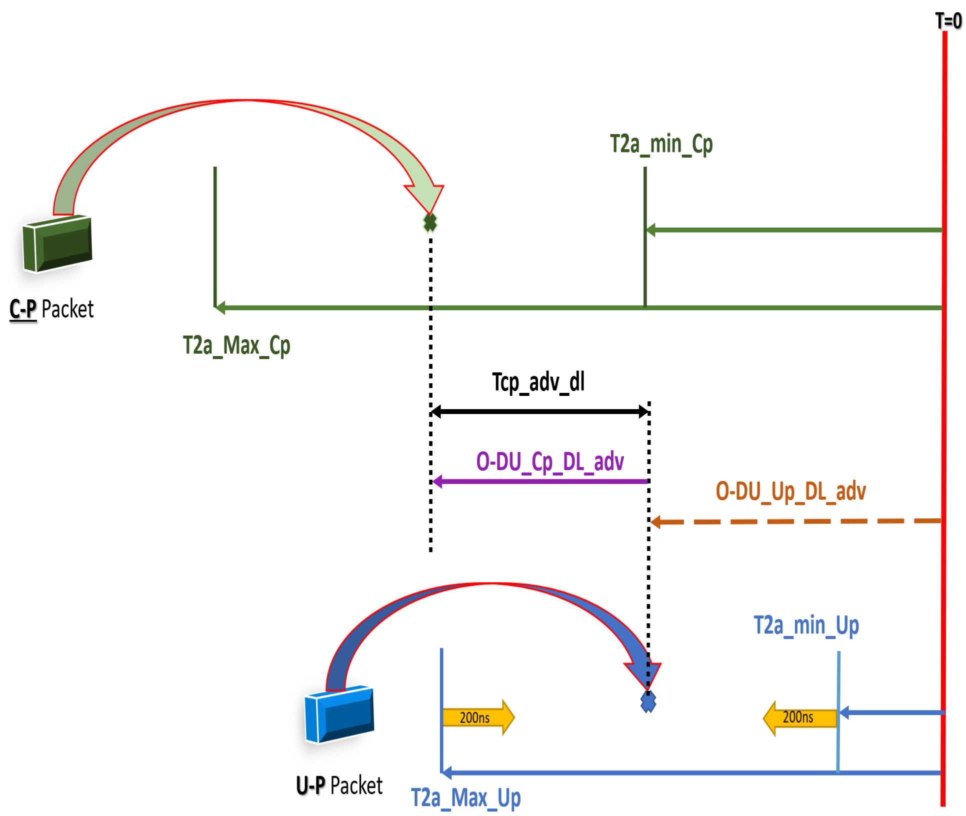

Figure 34. User plane at middle of reception window test plan.

b) Send User plane packets at 200ns after T2amax

The goal of this test case is to check the accuracy of O-RU timing reported value T2amax by sending the packets to be at exactly 200 ns after $\mathrm{T2a\_max\_up}$. In case we get IQ data this means accuracy defined by ORAN specifications is respected. To execute such a test the $\mathrm{ODU_{Up\_DL\_adv}}$ value should be changed in a way the User plane packet will arrive at 200ns after $\mathrm{T2a\_max\_up}$. Furthermore, the C plane packet should be sent at the middle of their window. The following formulas will be input to O-DU tester to perform such test case :

$$ODU_{\mathrm{Up\_dl\_adv}} = \mathrm{T2a\_max\_up} - 200 \tag{9}$$

$$ODU_{\mathrm{Cp\_dl\_adv}} = \mathrm{Tcp\_adv\_dl} - \frac{\mathrm{T2a\_max\_up} - \mathrm{T2a\_min\_up}}{2} + 200 \tag{10}$$

$\mathrm{ODU_{Up\_DL\_adv}}$ is set to be exactly at 200 ns after the starting of the reception window.

Moreover, C plane is kept to be sent at the middle of C plane reception window. To achieve such a goal, the time shift of the U plane from the middle of the window will be subtracted from the $\mathrm{Tcp\_adv\_dl}$ fixed value. The traffic is illustrated clearly in Figure 35

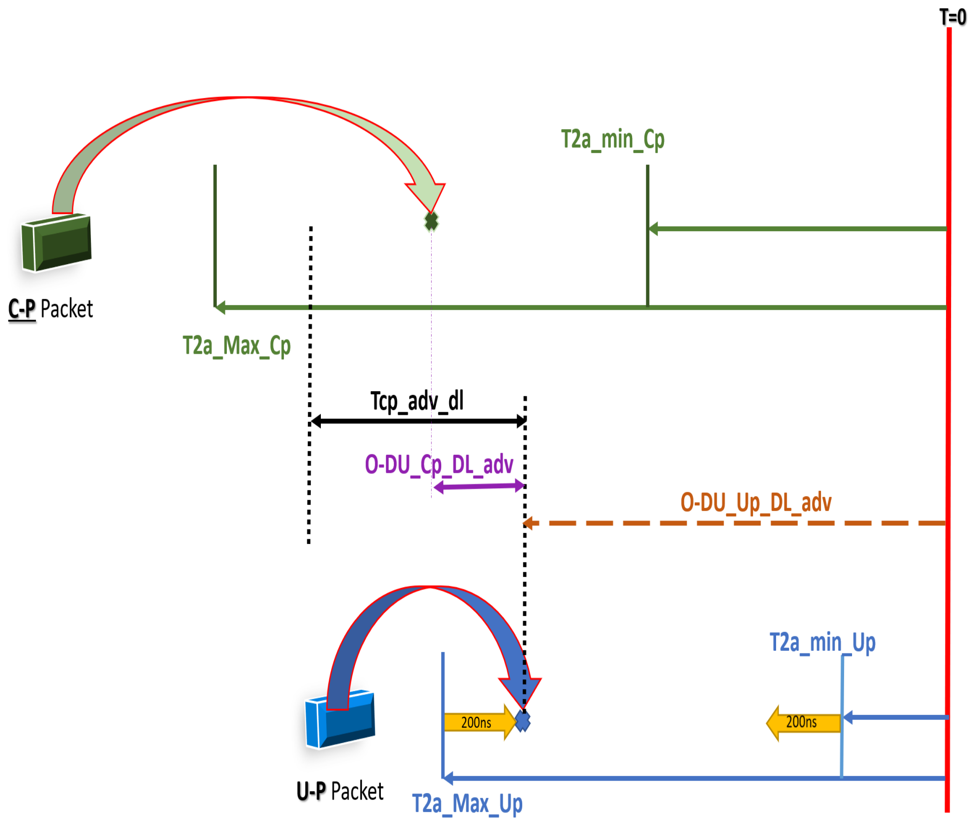

Figure 35. User plane at 200 ns after reception window start.

c) Send User plane packets at 200ns before T2a_min_up

The goal of this test case is to check the accuracy of the O-RU timing reported value T2a_min_up. The packet has been sent exactly 200 ns before the end of the Reception Window. As mentioned in the previous test case, both O-DU input parameters should be changed based on test cases criteria as depicted in Figure 36:

$$ODU_{\text{Up\_dl\_adv}} = \text{T2a\_min\_up} + 200 \tag{11}$$

$$ODU_{\text{Cp\_dl\_adv}} = \text{Tcp\_adv\_dl} + \frac{\text{T2a\_max\_up} - \text{T2a\_min\_up}}{2} - 200 \tag{12}$$

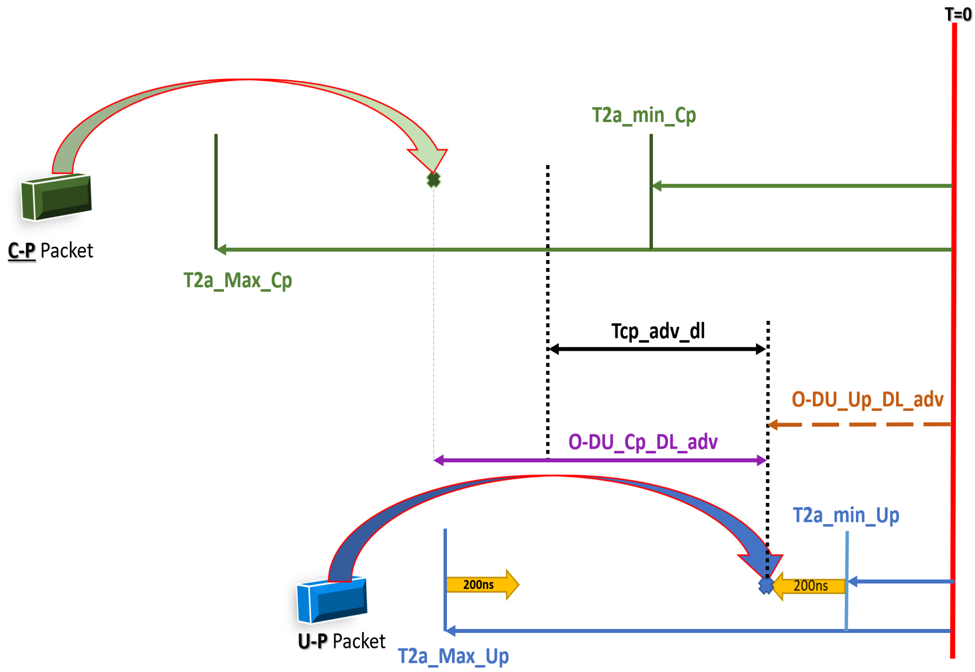

Figure 36. User plane at 200 ns before reception window end.

Phase 2 User plane Timing test Cases:

a)Send User plane packets outside the Reception window(Too Late)

The target of this test case is to send the User plane packet to be late such that it will be outside the Reception window. For this purpose, a time delay value is defined by Tout such that 0 μs < Tout <10 μs. Tout express how far the User plane is sent from the end of the reception window time $\mathrm{T2a\_min\_up}$(Figure 37) .

Same concept of the previous phase C plane should always be sent at the middle of their window. The following formulas are the key inputs for O-DU tester to perform such test case :

$$ODU_{\mathrm{Up\_dl\_adv}} = \mathrm{T2a\_min\_up} - Tout \tag{13}$$

$$ODU_{\mathrm{Cp\_dl\_adv}} = \mathrm{Tcp\_adv\_dl} + \frac{\mathrm{T2a\_max\_up} - \mathrm{T2a\_min\_up}}{2} + Tout \tag{14}$$

Based on the ORAN specification concerning the windows rules, a 0 IQ data should appear in the Signal analyzer Screen. We will discover the result in the next section.

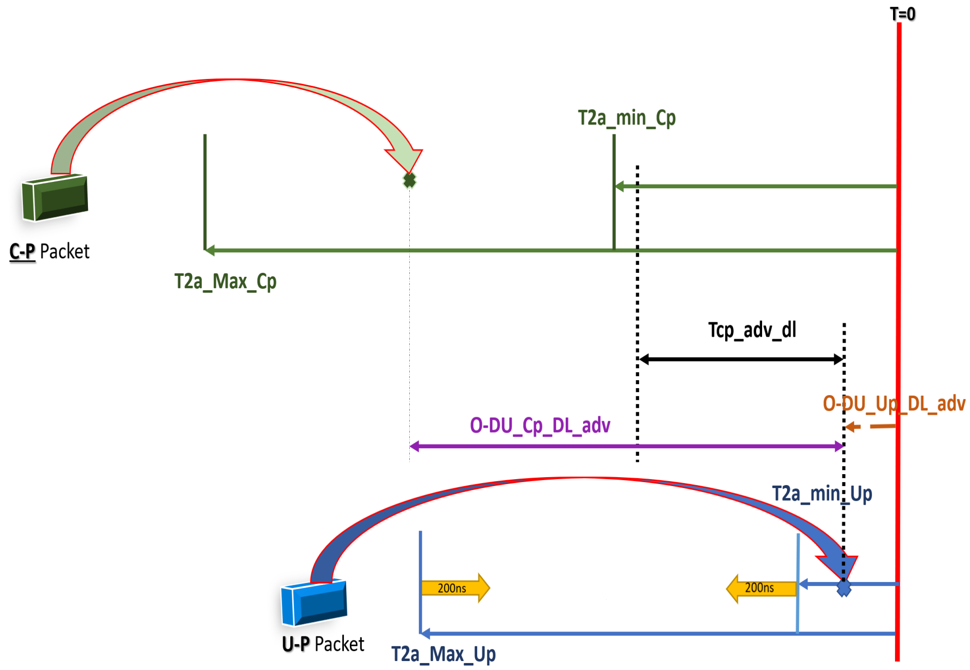

Figure 37. User plane sent too late.

b)Send User plane packets outside the Reception window(Too Early)

User plane packets are sent earlier than expected. In other words, they would arrive at O-RU earlier by Tout than the start of the reception window $\mathrm{T2a\_max\_up}$ by Tout amount of time(Figure 38). The following formula describes how the target of the test case is met

$$ODU_{\mathrm{Up\_dl\_adv}} = \mathrm{T2a\_max\_up} + Tout \tag{15}$$

$$ODU_{\mathrm{Cp\_dl\_adv}} = \mathrm{Tcp\_adv\_dl} - \frac{\mathrm{T2a\_max\_up} - \mathrm{T2a\_min\_up}}{2} - Tout \tag{16}$$

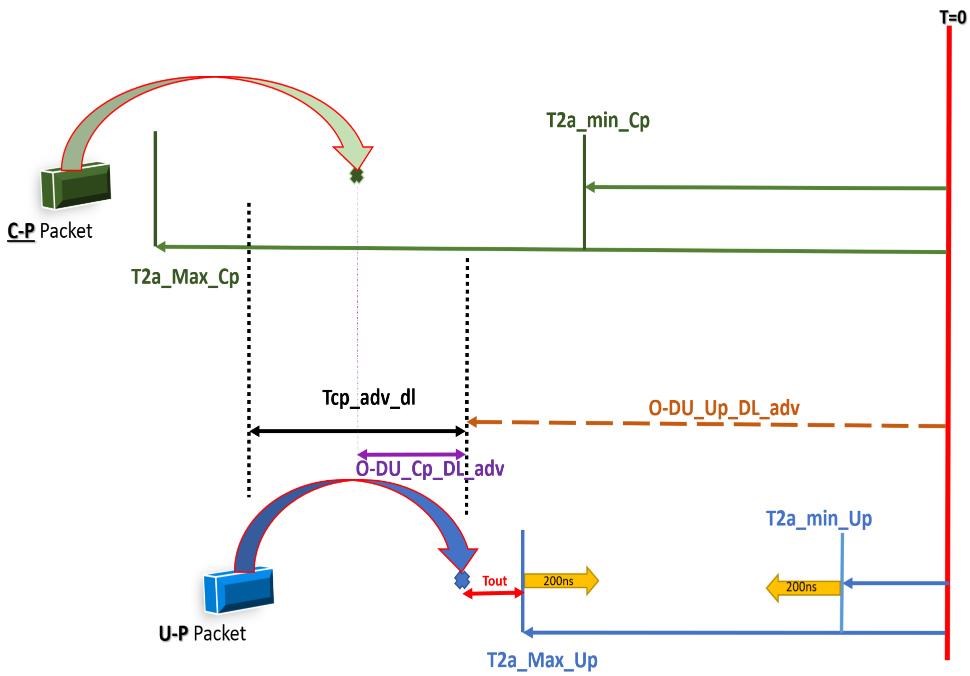

Figure 38. User plane sent too early.

6.1.2. Downlink Control Plane Test Cases

Control Plane test cases for downlink direction follow roughly the same steps and procedure done for the User plane. The test series concept is based on checking the Control plane reception window. In another word Control plane would change the time positions in and outside the control reception window defined by $\mathrm{T2a\_min\_cp}$ and $\mathrm{T2a\_max\_cp}$. Whereas, the User plane should be fixed in the middle of its reception window defined by $\mathrm{T2a\_min\_up}$ and $\mathrm{T2a\_max\_up}$. Figure 39 shows the different test cases designed for the Control plane timing test.

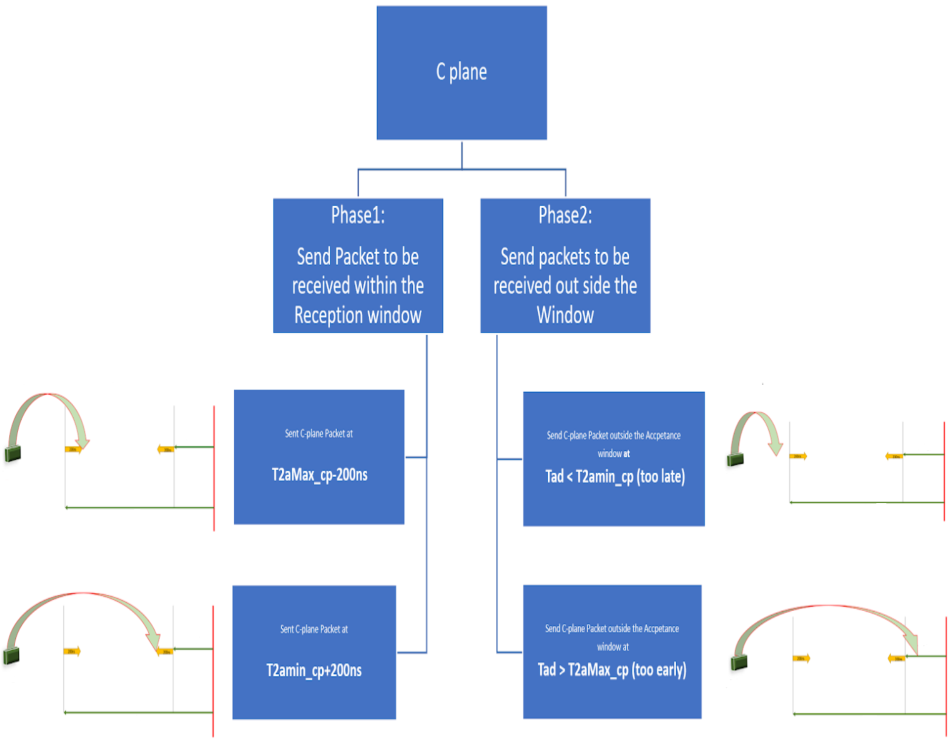

Figure 39. Downlink Control plane test plan.

Phase 1 Control plane Timing test Cases:

a) C plane sent at 200 ns after reception window start

Test case is described in Figure 40. it is performed using the following formulas :

$$ODU_{\text{Up\_dl\_adv}} = \frac{\text{T2a\_min\_up} + \text{T2a\_max\_up}}{2} \tag{17}$$

$$ODU_{\text{Cp\_dl\_adv}} = \text{Tcp\_adv\_dl} + \frac{\text{T2a\_max\_up} - \text{T2a\_min\_up}}{2} - 200 \tag{18}$$

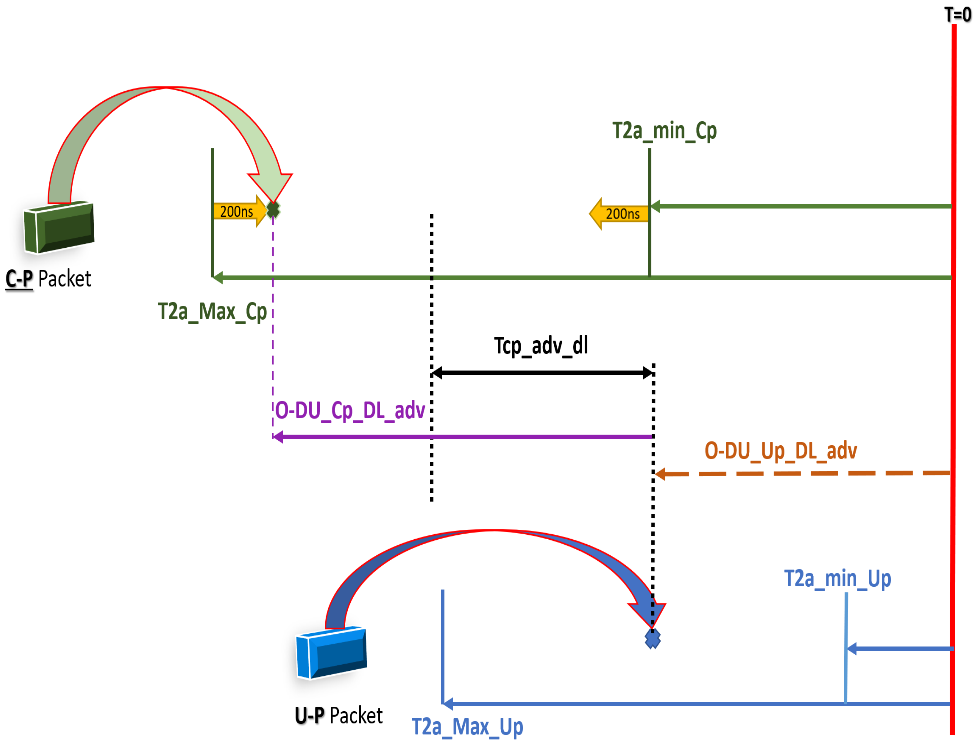

Figure 40. Downlink Control plane sent 200 ns after reception window start .

b) C plane sent at 200 ns after reception window start

Test case is described in Figure 41. it is performed using the following formulas :

$$ODU_{\text{Up\_dl\_adv}} = \frac{\text{T2a\_min\_up} + \text{T2a\_max\_up}}{2} \tag{19}$$

$$ODU_{\text{Cp\_dl\_adv}} = \text{Tcp\_adv\_dl} - \frac{\text{T2a\_max\_up} - \text{T2a\_min\_up}}{2} + 200 \tag{20}$$

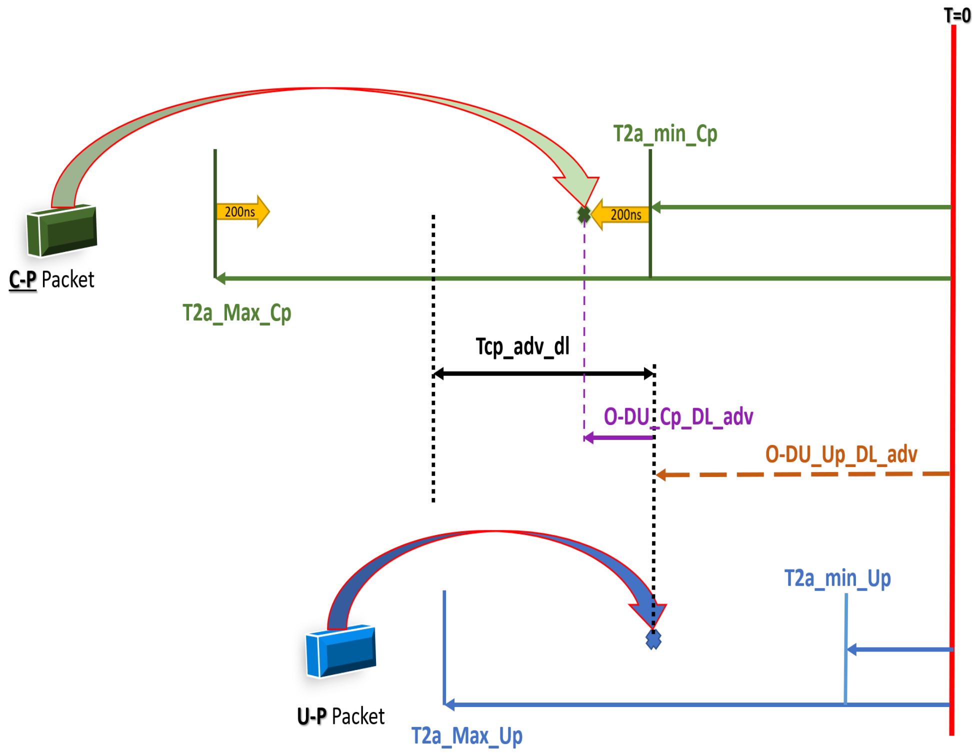

Figure 41. Downlink Control plane sent 200 ns before reception window end.

Phase 2 Control plane Timing test Cases

a) C plane sent too early

Test case is described in (Figure 42). It is performed using the following formulas :

$$ODU_{\text{Up\_dl\_adv}} = \frac{\text{T2a\_min\_up} + \text{T2a\_max\_up}}{2} \tag{21}$$

$$ODU_{\text{Cp\_dl\_adv}} = \text{Tcp\_adv\_dl} + \frac{\text{T2a\_max\_up} - \text{T2a\_min\_up}}{2} + Tout \tag{22}$$

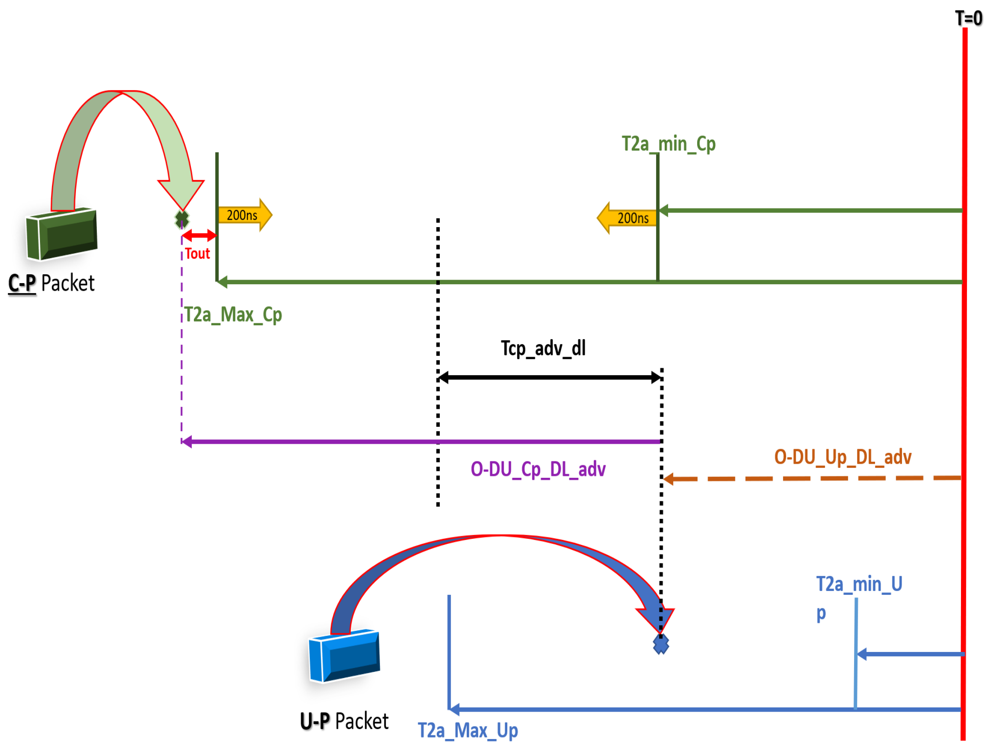

Figure 42. Downlink Control plane sent too Early.

b) C plane sent too Late

Test case is described in Figure 43. It is performed using the following formulas :

$$ODU_{\text{Up\_dl\_adv}} = \frac{\text{T2a\_min\_up} + \text{T2a\_max\_up}}{2} \tag{23}$$

$$ODU_{\text{Cp\_dl\_adv}} = \text{Tcp\_adv\_dl} - \frac{\text{T2a\_max\_up} - \text{T2a\_min\_up}}{2} - Tout \tag{24}$$

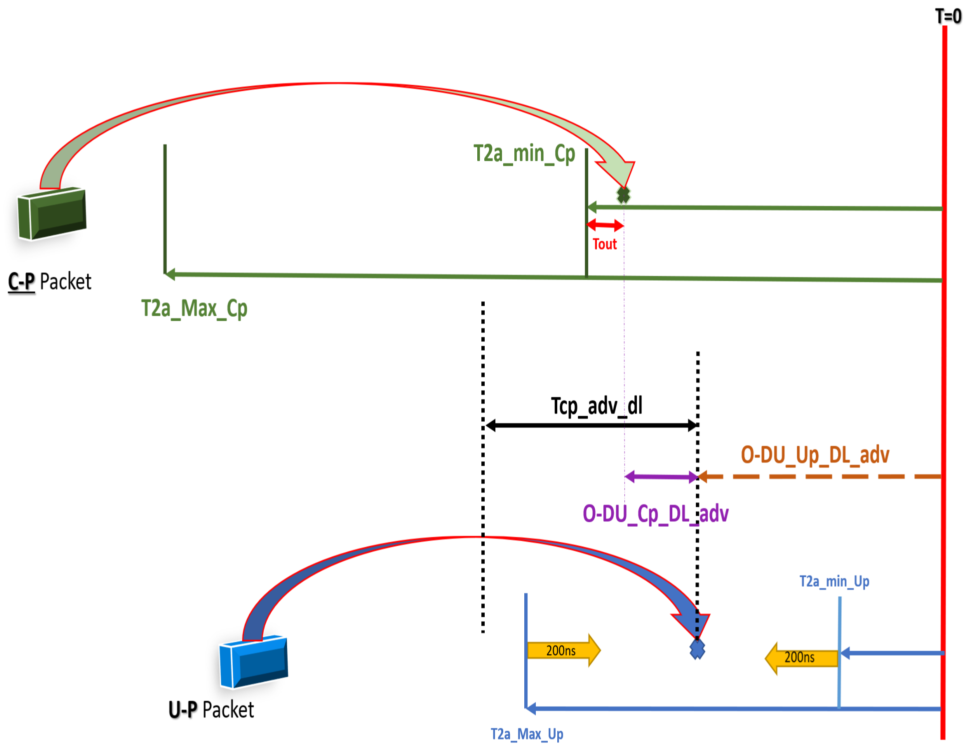

Figure 43. Downlink Control plane sent too late.

6.2. ECPRI Timing Uplink Test Cases

The uplink packet traffic is a bit different than the downlink. As depicted in Figure 29. Uplink Control plane is sent towards the O-RU transmitted from O-DU. So the transmission window of UL-CP is defined by $\mathrm{T2a\_min\_cp\_ul}$ and $\mathrm{T2a\_max\_cp\_ul}$. In contrast to downlink Control plane, the Uplink C plane Reception window is completely independent from the User plane of the same case. So, the only reference is the start transmission time of the air signal. Regarding Control plane test cases, the target would be to ensure their correct transmission within the O-RU reception window. The User plane in Uplink Direction tells a different story. In uplink, the O-RU receives a signal from user equipment going through antenna then processed and converted into several User plane packets. These packets could be transmitted starting at $\mathrm{Ta3\_min\_up}$ which indicates the start of the O-RU transmission window. The packets go through Fronthaul fiber cable where it will be delayed by T34. Uplink user plane data is transmitted to O-DU tester and should arrive within its Reception window, otherwise they will be discarded.

Typically, O-DU testers has no limit on Reception Window. The only flexible end is the start of Transmission window or the User Plane Offset parameter as defined in the O-DU tester Documentation. In other word, this parameter will be used as a variable for all Uplink user plane test cases. The Test setup illustrated in Figure 44 is built to perform all uplink timing test cases :

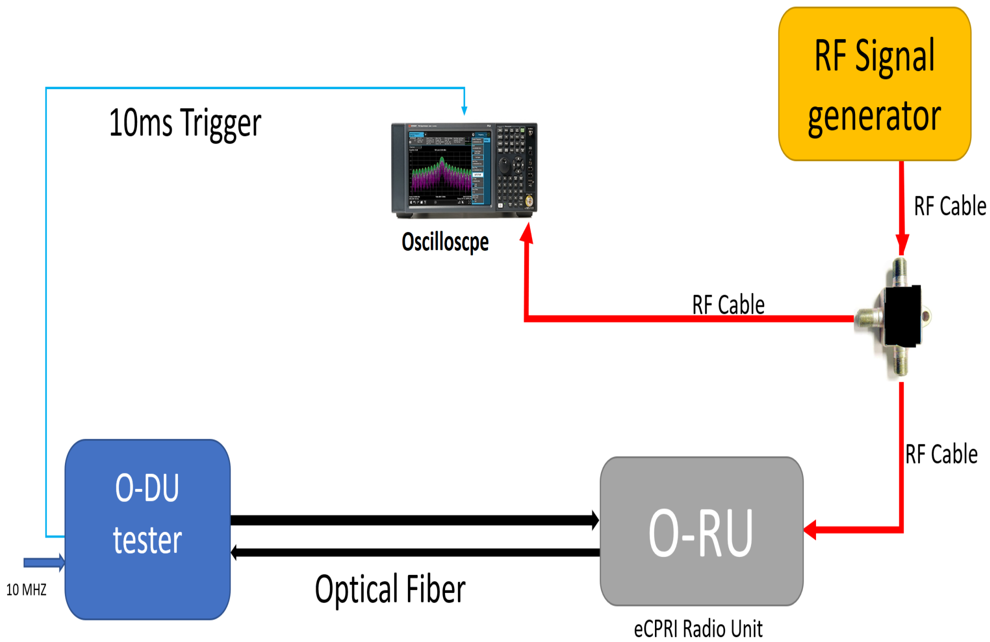

Figure 44. Downlink Test setup.

6.2.1. Uplink Control Plane Test Cases

Uplink control plane test cases are the similar to the downlink ones; the only difference is reception window and formula used for test execution. During the Control plane test cases in Uplink , the Reception Window of the User Plane in O-DU should be constant. In other word UP UL Offset should be constant in all test cases .

a) Control plane sent in the Middle of reception window

Test case is described in Figure 45. It is performed using the following formulas :

$$ODU_{\text{Cp\_ul\_adv}} = \frac{\text{T2a\_min\_cp\_ul} + \text{T2a\_max\_cp\_ul}}{2} \tag{25}$$

$$ODU_{\text{Up\_Ul\_adv}} = \text{T3a\_min\_up} + T34 \tag{26}$$

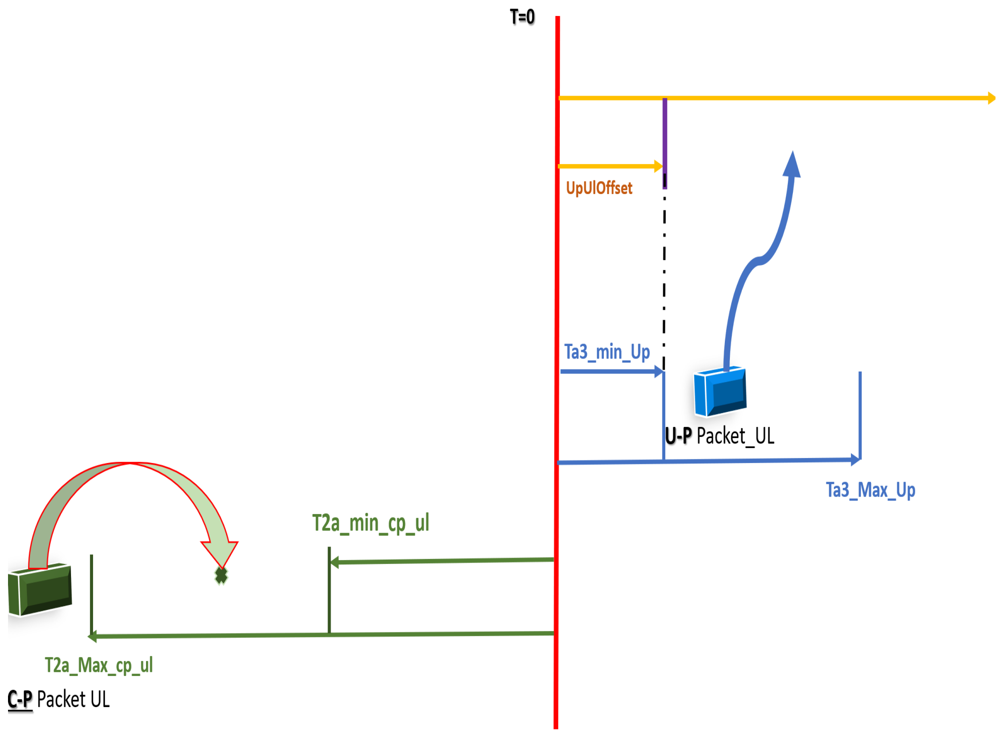

Figure 45. Uplink Control plane sent middle of reception window .

b) Control plane sent 200 ns before reception window end

Test case is described in Figure 46. It is performed using the following formulas :

$$ODU_{\text{Cp\_ul\_adv}} = \text{T2a\_min\_cp\_ul} + 200 \tag{27}$$

$$ODU_{\text{Up\_Ul\_adv}} = \text{T3a\_min\_up} + T34 \tag{28}$$

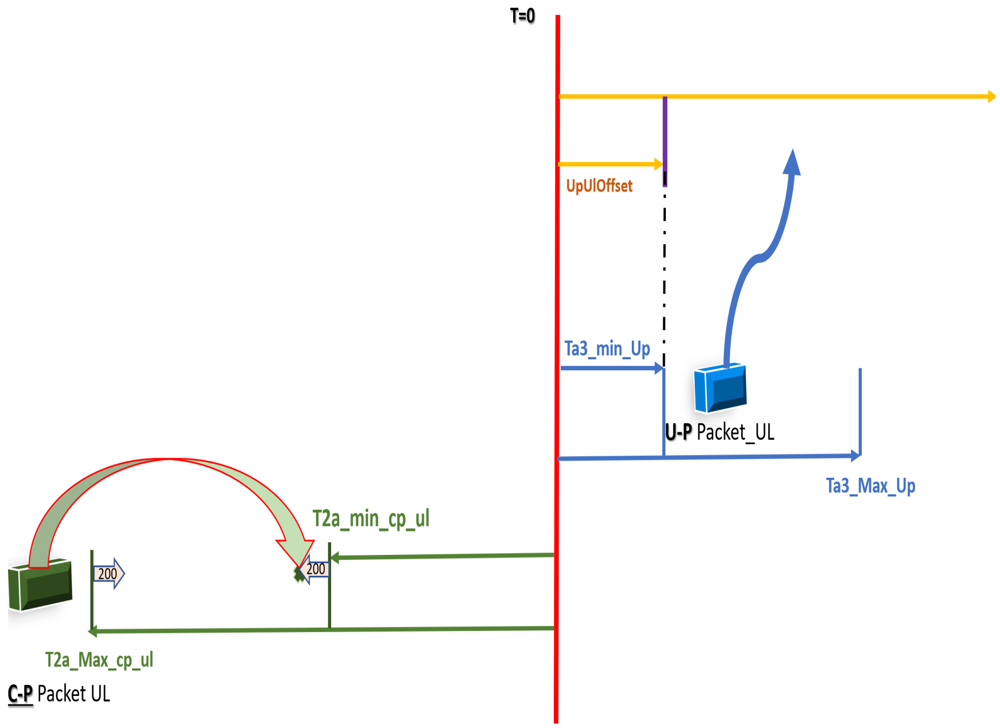

Figure 46. Uplink Control plane sent 200 ns before reception window end .

c) Control plane sent 200 ns after reception window start

Test case is described in (Figure 47). It is performed using the following formulas :

$$ODU_{\mathrm{Cp\_ul\_adv}} = \mathrm{T2a\_min\_cp\_ul} + 200 \tag{29}$$

$$ODU_{\mathrm{Up\_Ul\_adv}} = \mathrm{T3a\_min\_up} + T34 \tag{30}$$

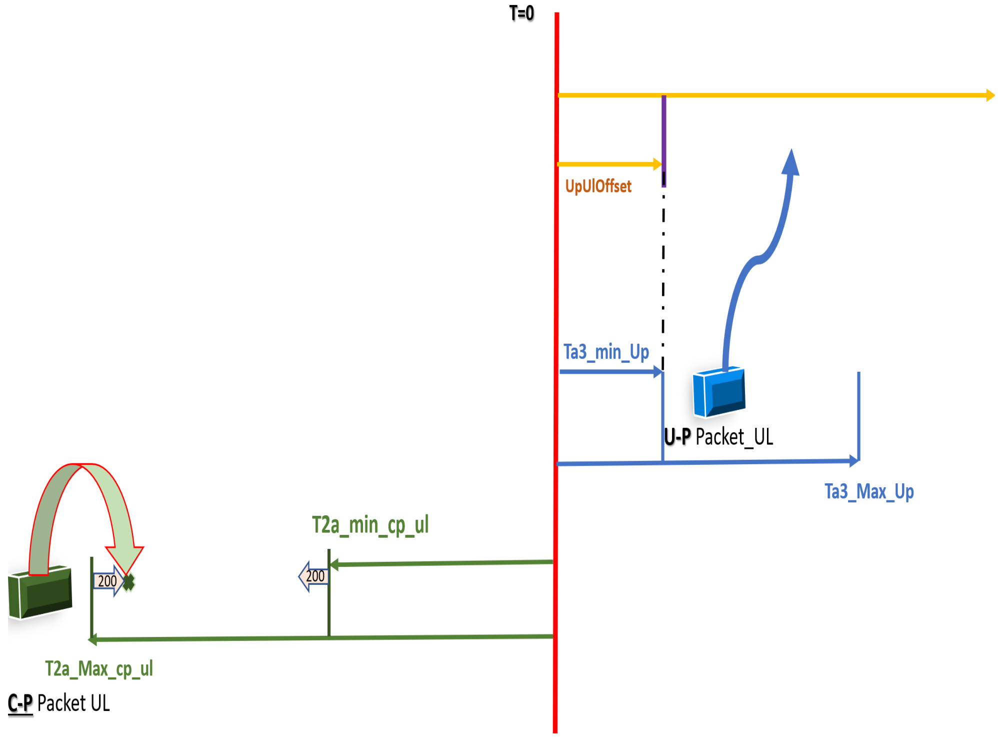

Figure 47. Uplink Control plane sent 200 ns after reception window start .

d) Control plane sent too late

Test case is described in Figure 48. It is performed using the following formulas :

$$ODU_{\text{Cp\_ul\_adv}} = \text{T2a\_min\_cp\_ul} - Tout \tag{31}$$

$$ODU_{\text{Up\_Ul\_adv}} = \text{T3a\_min\_up} + T34 \tag{32}$$

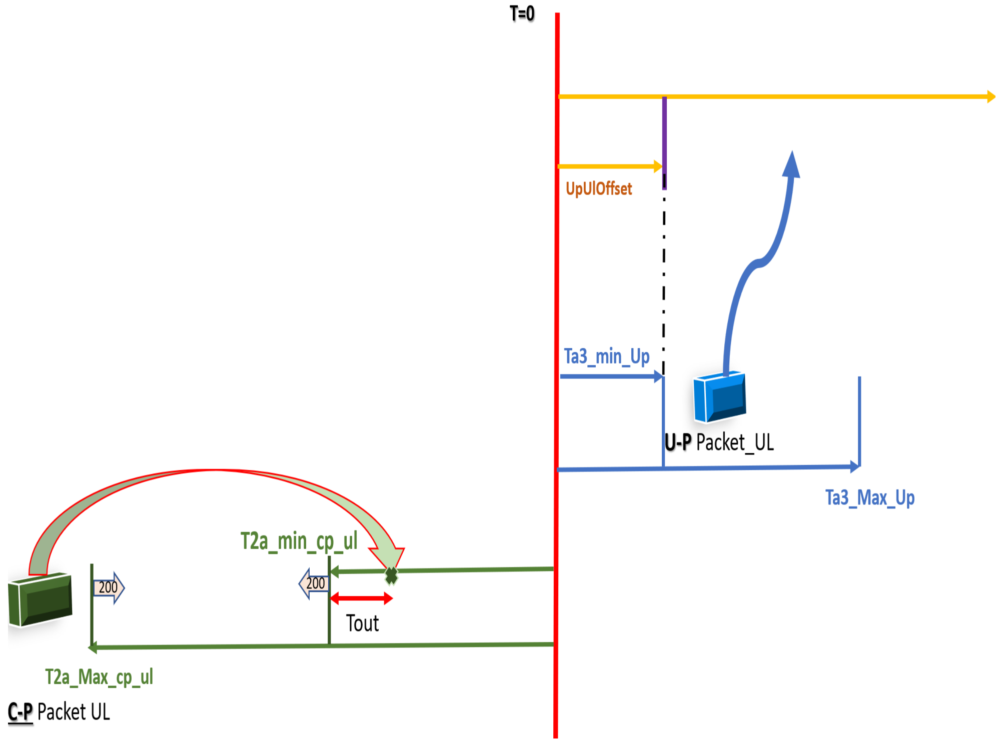

Figure 48. Uplink Control plane sent too late .

e) Control plane sent too early

Test case is described in Figure 49. It is performed using the following formulas :

$$ODU_{\text{Cp\_ul\_adv}} = \text{T2a\_min\_cp\_ul} + Tout \tag{33}$$

$$ODU_{\text{Up\_Ul\_adv}} = \text{T3a\_min\_up} + T34 \tag{34}$$

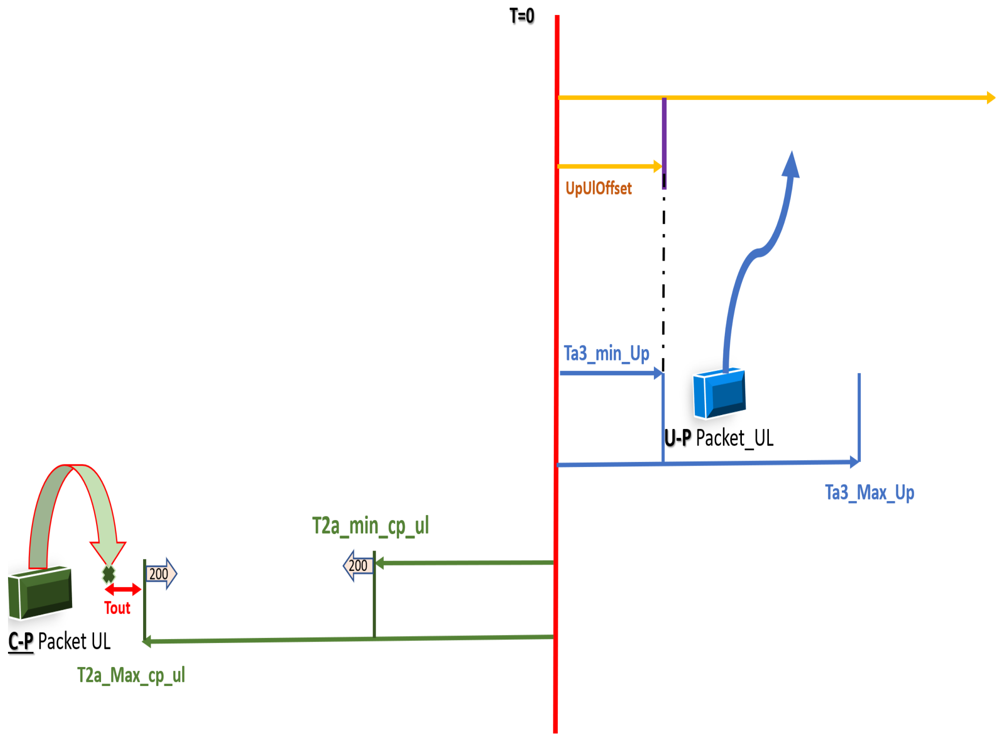

Figure 49. Uplink Control plane sent too early .

6.2.2. Uplink User Plane Test Cases

For the user plane, uplink Packets are transmitted from O-RU to O-DU tester. Unfortunately there is no possibility to change the O-RU transmission time. Therefore, we noticed the flexibility of the O-DU reception window can stimulate us to achieve the target . Indeed ,our goal for this test bench is to just confirm the accuracy of O-RU Transmission window Timing parameters (Ta3_min_up and Ta3_max_up). The next two subsections will describe the procedure.

a)Set O-DU tester reception window start 200ns earlier than T3a-min-UP

The purpose of this test case is to evaluate the accuracy of Ta3_max_up Figure 50. To perform such test case the following formulas are used as input for O-DU tester :

$$ODU_{\text{Cp\_ul\_adv}} = \frac{\text{T2a\_min\_cp\_ul} + \text{T2amax\_cp\_ul}}{2} \tag{35}$$

$$ODU_{\text{Up\_Ul\_adv}} = \text{T3a\_min\_up} + T34 - 200 \tag{36}$$

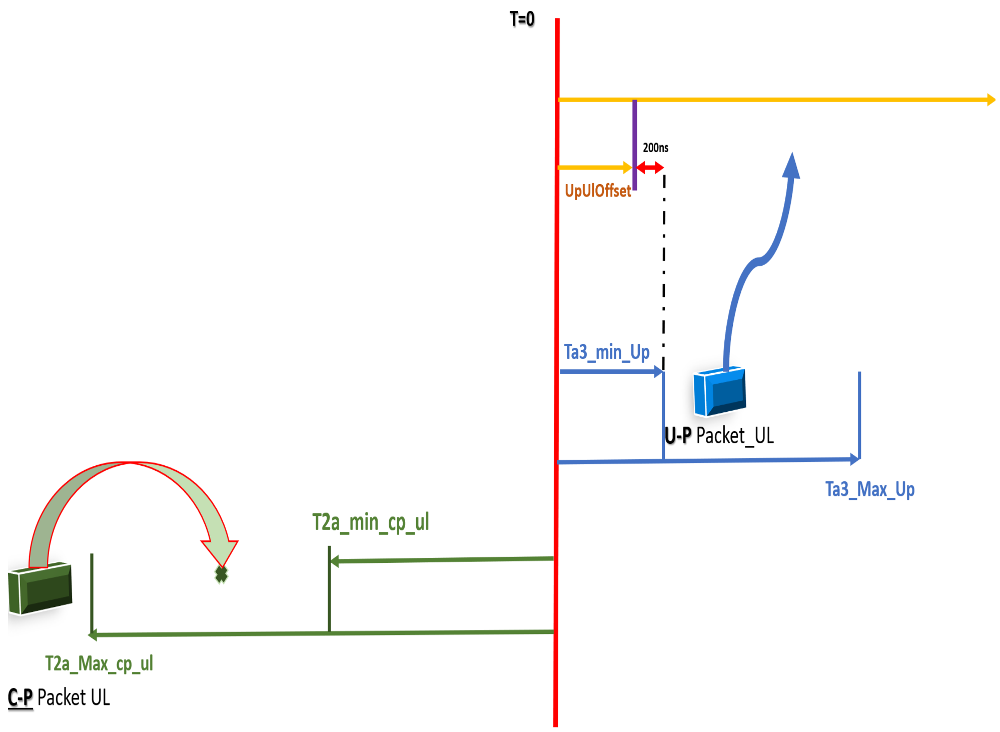

Figure 50. Set Reception Window 200ns earlier than expected .

b)Set O-DU tester reception window start 200 ns later than Ta3 Max Up

In this test case, the Ta3 min Up parameter accuracy is verified. These parameters define the earliest time when the Radio unit can start sending user plane packets to O-DU tester.(Figure 51). By varying the start reception time in O-DU (purple line) we can approximately know if the Ta3_min_up is respected or not . At the same time we try to maximize the number of packets sent From O-RU at least to stimulate the radio to start sending the packets Late (close to Ta3_max_up) . To perform such test case the following formulas are used as input for O-DU tester :

$$ODU_{\text{Cp\_ul\_adv}} = \frac{\text{T2a\_min\_cp\_ul} + \text{T2amax\_cp\_ul}}{2} \tag{37}$$

$$ODU_{\text{Up\_Ul\_adv}} = \text{T3a\_max\_up} + T34 + 200 \tag{38}$$

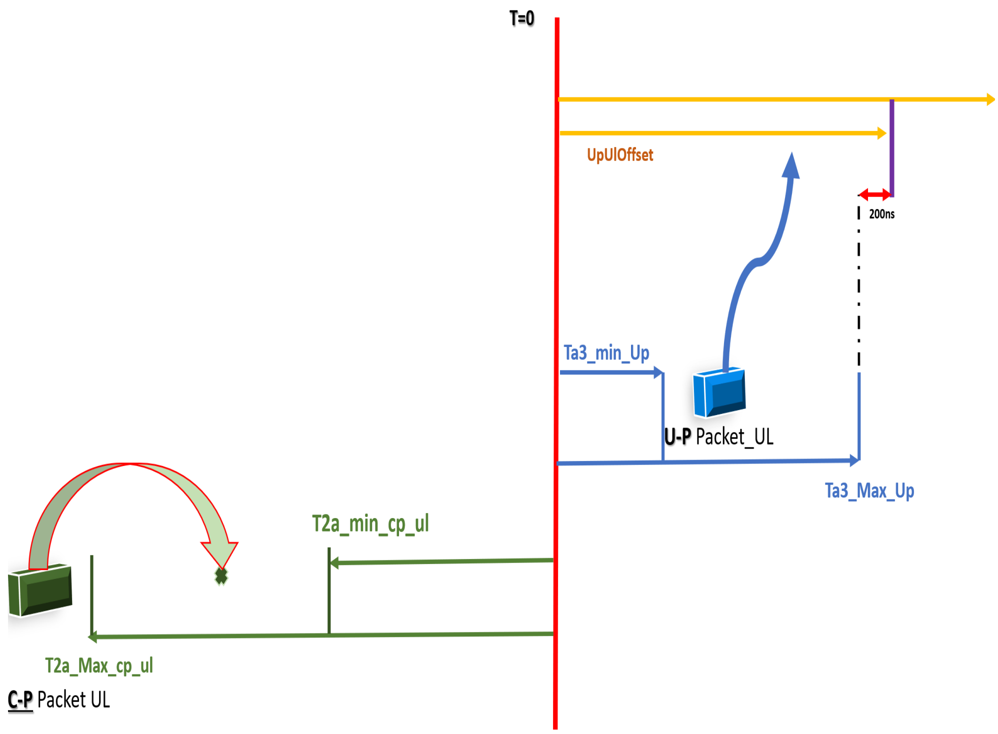

Figure 51. Set Reception Window 200ns Later than expected .

6.2.3. Pass/ Fail Timing Test Criteria

After performing all precedent test cases the resulting signal from the antenna will be further analyzed to decide pass or fail status . In the following subsection, an algorithm is designed for each series of tests depending on the direction, either uplink or downlink.

Downlink test criteria:

For downlink test cases, the test result decision will be divided into two parts. The first is phase 1 specific, Figure 52whereas the second is for phase 2 Figure 53. The two parts combine both user plane and control plane test cases.

In phase 1, the packets are expected to be received inside the reception window defined by T2amin and T2amax. Based on ORAN specification, the expected result is always correct IQ data out from antenna. Consequently, if wrong IQ data is received, the test case will be considered as a failure. The root cause of the issue should be investigated.The correctness of IQ data is described by EVM. If the EVM value is less than maximum expected then IQ data is correct else it is just noise or erroneous .

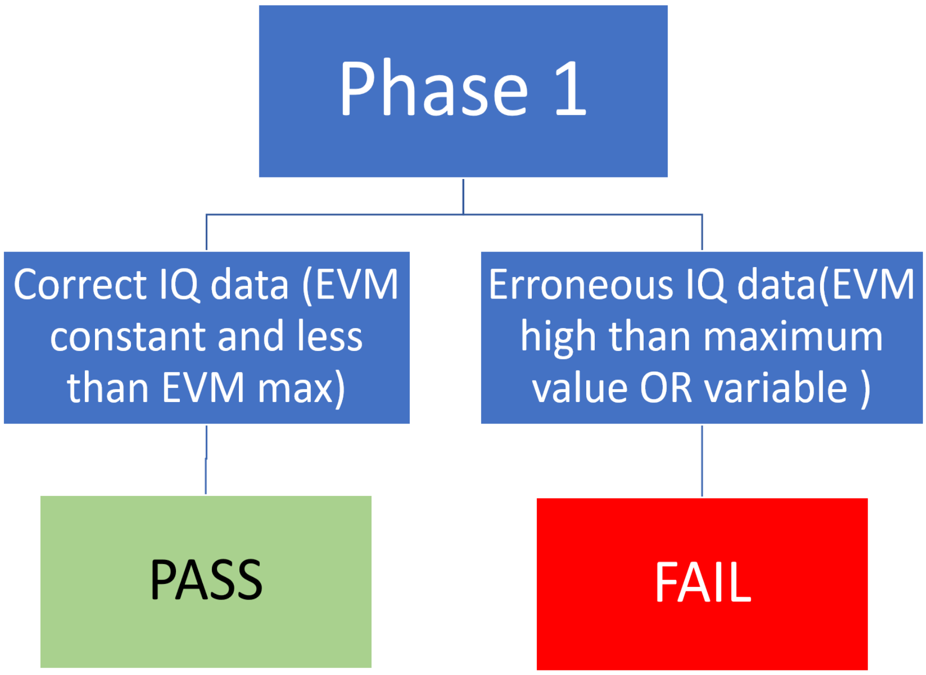

Figure 52. Downlink Phase 1 test criteria.

Whereas phase 2 test criteria branches first into 3 cases. Firstly , erroneous IQ data is detected implies to fail test case. Secondly, correct IQ data with a suitable EVM value. In this case the Late/Early counter status should be checked. Supposing the counter increments. That means some packets has been detected outside RU reception window, then the test fails. If the counter status is constant, this means all packets were received within RU reception window, as a result the test case passes.

Finally, if 0 IQ data is resulted and counter content increments ; signifies that the Radio Unit detects the late or early reception of packets thus the test passes . However, in case that counter status is constant, it indicates a miss detection of packet received outside the window so the test fails.

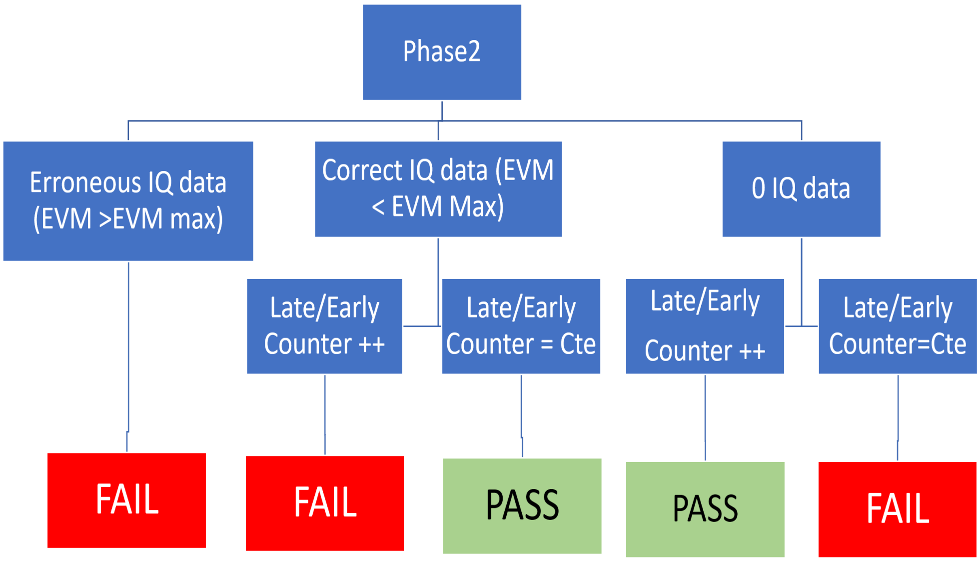

Figure 53. Downlink Phase 2 test criteria.

Uplink test criteria

Uplink Control plane test criteria

As the control plane in uplink follows in the same direction as in downlink(see Figure 52and Figure 53, it will follow the same test criteria defined in downlink. The two unique difference are :
a) the reception window is defined by a specific timing parameter to control plane uplink defined by $\mathrm{T2a\_max\_cp}$ and $\mathrm{T2a\_min\_cp}$.
b) The captured IQ data should be correlated with the reference signal. The RF signal generator's output is set to be the reference signal in this test scenarios.

Uplink Control plane test criteria

In the uplink user plane criteria, we are expecting to get capture with correct IQ data by the O-DU tester. In other words, all the transmitted packets should be received correctly. Otherwise ,the test will fail(similar to Figure 53)

6.3. Test Strategy and Results

The success of the algorithm can be measured following a good test strategy. As mentioned at the beginning of this thesis, the goal of the algorithm implementation is to examine the Radio Unit from timing perspective. In other words. our eCPRI Timing Measurement implementation should report a pass status when all ORAN timing requirements are matched in the Radio Unit.

Table 11: Units under test characteristics

Test Case	Radio Unit software characteristics
DL_UP at Window Centre	*Downlink User plane Reception window following ORAN specification*
DL_UP at T2amin+200ns	*Downlink User plane Reception window following ORAN specification*
DL_UP at T2amin-200ns	*Downlink User plane Reception window following ORAN specification*
DL_UP too Late	*Radio Unit process data packets even received outside User plane reception window*
DL_UP too Early	*Radio Unit process data packets even received outside User plane reception window*
DL_CP at T2amin_cp +200ns	Downlink control plane reception window Following ORAN specification
DL_CP at T2amax_cp -200ns	Downlink control plane reception window Following ORAN specification
DL_CP too Late	Radio Unit process Control plane data regardless of the reception window limit
DL_CP too Early	Radio Unit process Control plane data regardless of the reception window limit
UL_CP at middle at Window Centre	Uplink Control plane reception window following ORAN specification but with High EVM
UL_CP at T2amax_cp_ul -200ns	Uplink Control plane reception window following ORAN specification but with High EVM
UL_CP at T2amin_cp_ul +200ns	Uplink Control plane reception window following ORAN specification but with High EVM
UL_CP Too Late	Uplink Control plane reception window does come after ORAN specification
UL_CP Too Early	Uplink Control plane reception window does not come after ORAN specification
UL_UP reception T3amin -200ns	Uplink User plane transmission window following ORAN specification but with High EVM
UL_UP reception T3aMax +200ns	Uplink User plane Transmission window does not come after ORAN specification

Moreover, when one of the timing requirements are not respected in the Radio Unit, the algorithm mechanism should detect and report it as Fail test case. A strategy has been followed to check the algorithm characteristic in the test as follows. The first test series loads different software packages to the Radio Unit. Each RF software should have a missing feature. So, we execute the test case and see if the specific bug has been detected.If the problem has been detected means it is true positive result. Otherwise, if the test passes and no bug has been noticed. Then it is a false positive.

For the other series of tests. we load a software package that allows Radio unit to respect the ORAN specifications' timing .If the test Passes and no problem has been detected it is a true positive test. In case a problem has been detected and the test fails implies a wrong interpretation of the situation and this is false negative case. Table 11 defines each test case and the missing and existing feature of the Radio unit software used.

Table 12: True positive and True negative results

Test Case	Expected Result		Actual Result		Status
	EVM Value (%)	E\L Counters	EVM Value (%)	E\L Counters	
DL_UP at Window Centre	EVM < 9	Constant	6.22	Constant	PASS
DL_UP at T2amin+200ns	EVM < 9	Constant	4.73	Constant	PASS
DL_UP at T2amax-200ns	EVM < 9	Constant	7.24	Constant	PASS
DL_UP too Late	EVM > 9	Incrementing	236.44	Incrementing	FAIL
DL_UP too Early	EVM > 9	Incrementing	229.51	Incrementing	FAIL
DL_CP at T2amin_cp +200ns	EVM < 9	Constant	2.3	Constant	PASS
DL_CP at T2amax_cp -200ns	EVM < 9	Constant	2.5	Constant	PASS
DL_CP too Late	EVM < 9	Constant	4.19	/	FAIL
DL_CP too Early	EVM < 9	Constant	2,5	Constant	FAIL
UL_CP at middle at Window Centre	EVM < 50	/	29.91	/	PASS
UL_CP at T2amax_cp_ul -200ns	EVM < 50	/	29.83	/	PASS
UL_CP at T2amin_cp_ul +200ns	EVM < 50	/	35.82	/	PASS
UL_CP Too Late	EVM < 50	/	29.83	/	FAIL
UL_CP Too Early	EVM <50	/	29.81	/	FAIL
UL_UP reception T3amin -200ns	EVM < 50	/	8.8	/	PASS
UL_UP reception T3aMax +200ns	EVM < 50	/	8.9	/	FAIL

In Table 12 example of the results where the algorithm has successfully validated the case, or detected the problem by declaring the failure of the test case. Based on two previous tables, Table 13 will describe the status of algorithm test cases by classifying the test cases in 4 different categories (true positive, true negative, false positive, false negative). Furthermore, for every test case, at least 3 different tests have been conducted.

Table 13: Algorithm test result classification

	All test cases	True Positive	True Negative	False Positive	False Negative
Downlink test cases	45	23	20	0	2
Uplink test cases	28	16	11	1	0
Entire Algorithm test cases	73	39	31	1	2

Finally, in Table 14 accuracy, sensitivity and specificity of the algorithm are calculated. Based on the results in the last table, the performance of the algorithm will be evaluated.

Table 14: Test result evaluation

	Sensitivity (%)	Specificity (%)	Accuracy (%)
Downlink Test Cases	92	100	95.55
Uplink Test Cases	100	91.66	96.42
Entire Algorithm test cases	95.12	96.87	95.89

7. DISCUSSION

In this chapter, the results depicted earlier will be analyzed and justified. The evaluation of the entire algorithm will also be conducted next. Constructive criticism and the developed future proposition would be sited last. As mentioned in the result section, the test strategy was designed to check robustness of the algorithm and test strategy in detecting timing related issues in an RU. Based on Table 11, the results shown in the Table 12 will be analyzed one test case at a time.

Starting by 'DL_UP at Window Centre' where the user plane has been sent at the middle of the reception window, correct IQ data are transmitted over the antenna. So EVM should be less than the maximum value, since we are testing on Radio Unit that follows ORAN specification regarding downlink user plane reception window. Moreover, the early late counter should be constant (see Figure 53). As shown in Table 12, in the actual and expected result matches each other so that EVM =6.22 and the counters are constant. The final algorithm results indicate that the test is passed. The test result is classified as a true Positive case. Some observations on the next two test cases 'DL_UP at T2amin+200ns' and 'DL-UP at T2amin-200ns' which were conducted on an RU that complies with ORAN specifications. The results were same as we expected then the tests pass.

In 'DL_UP too Late' test case the U plane packet has been sent to be received outside the RU reception window to be too late (see Figure 37). The conduction of this test case was performed on RU with a software that does not follow ORAN specification. More specifically, even if the packets arrives too late, they will be processed by the RU. As a result erroneous IQ data is sent out from the antenna and the test should Fail (see Figure 53). For this reason, in the actual result we get a high EVM (indicating wrong IQ data) and counter increments (indicate late reception of the packets). For sure the test cases should fail. The same logic happens for 'DL-UP too Early' test the only difference is the packets are sent too early although the Radio Unit is able to process them instead of discarding them. Both test cases are classified as True Negative.

Switching to control plane downlink test cases, we started the execution by 'DL_CP at T2amin_cp +200ns' and 'DL-CP at T2amax_cp -200ns'. In both test cases the Control plane downlink reception window requirements were satisfied on the Radio unit under test. Hence the test case has been passed and the actual result was matching the expected one.

However, in the 'DL_CP too Late' and 'DL_CP too Early' test cases we sent the control plane packets outside its reception window. Typically, based on ORAN timing specification, the Radio unit behavior would be as follows: first the control plane packets arrived early or late will be thrown out and never processed. At the same time, any User plane packet is not taken into consideration in all cases even if they are received inside their window. However, we executed the test on the Radio unit where control plane packets are accepted and processed even if they are too late or too early. This Explains the actual result we get represented by Correct IQ data out. Indeed, both test cases failed because the delay management requirements are not respected.

Moving to uplink test cases. The first three test cases, relative to the control plane in uplink direction are performed on a RU with software which respects ORAN timing specification. The actual result interprets the correctness of the IQ data received by O-DU tester then the test passes. Although, the test cases 'UL-CP Too Late' and

'UL_CP Too Early' the uplink control plane has been sent to be outside the reception window. In the regular state, the radio unit should not process any control plane data. This implies that uplink user plane packets are neither produced nor sent to the O-DU tester. Due to the lack of this requirement in the device under test, user plane packets with correct IQ data are received by the O-DU tester which means the failure of both test cases.

'UL_UP reception $T3a\_min - 200ns$' test case passes as the Radio Unit sent the User plane packet after the T3amin -200ns. This indicates the following of ORAN specification by the RU we are testing. However, in the last test case we adapted the O-DU tester to start accepting the user plane packet starting from the end of the transmission window. In usual cases we expect no user plane packet to be received, but it was not the case here so that the O-DU has received the user plane packets and with correct IQ data.

A total of 45 tests has been executed for Downlink direction (5 for each test case). The group of tests is classified in Row 1 of Table 13.

23 tests have been classified as true positive cases. This means that the Radio unit has no problem regarding those test cases and the Algorithm has validated and Passed the test.

Test cases 1, 2, 3, 6 and 7 are concerned with this result. On the other hand, 2 tests have been incorrectly classified by the algorithm. In this case, the Radio was working properly but the algorithm reported an existing problem. As a result, the two test cases are in false negative column. Furthermore, test cases 4, 5, 8 and 9 have been perfectly examined, and in all 20 executed tests the algorithm has detected the existing problem and missing feature in the Radio unit.

In Uplink direction, 4 tests have been executed. For each test case and ended up with a total of 28 experiments. In practice, test cases 13,14 and 16 are executed on radio modules with different missing features. Then, the algorithm should detect the problem and the test should fail. This scenario was followed in 11 tests except the last one where the issue was not detected and the test passed. This implies 11 true negative and 1 false positive. Moreover, all the remaining uplink test cases were correctly examined, and the result is 16 True positive. Finally, the entire algorithm result illustrated in the third row of Table 13 with a total of 73 tests executed. 39 true positive, 31 true negatives, 1 false-positive and 2 false-negative results. In Table 14, we end up evaluating the test algorithm relative to sensitivity, specificity, and accuracy. For the entire algorithm tests, sensitivity was 95.12% this result means the algorithm was certain to validate the test cases and only 4,88% of uncertainties was noticed (due to the 2 false-negative results where the algorithm was not certain in that case). Regarding specificity, a perfect result of 96.87 shown in the table as all the true negative results were correctly classified except one in the uplink. Lastly, the 73 test results accuracy is 95.89% demonstrates the high precision on correctly classifying instances.

After analyzing the test result, we conclude that the algorithm examiner of timing ORAN specification was successfully working. Furthermore, the interpretation by the sensitivity, specificity, and accuracy clarifies the performance and high precision of the test algorithm. Thus, from 73 tests only 3 tests were incorrectly examined. Due to the wide world of 5G technology, it is hard to enclose all the features. For example, in a mixed numerology case, the algorithm needs more improvement and more test cases should be defined. Moreover, synchronization between O-DU and O-RU is one of the important requirements for data follow insurance. However, this was out of the scope of this thesis. The effect of it should have an impact on the accuracy of the timing when we specify to send the packet and the time when it is received because the two are not accurately aligned to the same time reference. Finally, the internal clock accuracy of both O-DU and O-RU was not taken into account. This could variate the timing result and force the Radio Unit to behave improperly. In such case, the algorithm would fail in its examination.

Future work related to the project will focuses on 3 main areas. First, defining more test cases related to synchronization accuracy between O-DU and O-RU . Second, set timing test cases to verify air frame signal timing delay . Third, build an automation tool to cover all test cases for O-RU with eCPRI interface

Comparing to timing measurement in CPRI protocol. CPRI is a synchronous interface with strictly periodic scheduling of data (basic frames) and a timing marker (CPRI frame marker K28.5), which makes the definition of delays and consequently timing measurements rather straight forward. However, eCPRI data transport is more statistical, there is no fixed timing marker in the protocol so sync has to be done via other means (PTP), which has impacts to timing and delay definition and timing measurement methods.

8. SUMMARY

After months of hard work, the main objective of this project work has been achieved. As mentioned in the introduction, the purpose of this thesis is to end up with a mechanism or an algorithm which is capable of examining and validating the 5G Radio unit from a timing point of view. To get familiar better with 5G base station and their new radio technology, Chapter 1 included a general description of 5GNR and Baseband Unit functionalities as well as the synchronization in between. In the next chapter, Open Radio Access Network basics were introduced including its architecture and efficiency of its services. Coming closer to the subject, Chapter 3 was consistent with 5G fronthaul. both CPRI and eCPRI protocols were described in detail. Chapter 4 focuses only on the Timing topics. This chapter can be considered as the theory part of the implementation. In that chapter, the timing concept and ORAN timing requirement were mentioned as well as the data traffic within the eCPRI fronthaul from a timing perspective. In the implementation chapter (Chapter 5), the algorithm structure and more related details where present. The algorithm design was based on ORAN delay management specification where the radio should fulfill them all in order to be validated by our test algorithm. The algorithm was branched out into 16 test cases divided between downlink and uplink direction. 73 tests have been executed following an efficient test strategy to evaluate our algorithm performance and precision. All the results were illustrated in different tables. With sensitivity of 95.12%, a specificity of 96.87%, and an accuracy of 95.89% our algorithm demonstrated its high performance and precision.

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